# TelePACE PID Controllers

User and Reference Manual

**CONTROL MICROSYSTEMS**

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## TelePACE PID Controllers User and Reference Manual

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# TelePACE PID Controllers Overview

The PID (Proportional, Integral, Derivative) control algorithm has been used for feedback control systems since the turn of the century. Traditionally, pneumatic controllers were used to perform this algorithm. Though easy to use, they are limited as to the additional functions that can be performed.

Electronic PID controllers expanded the versatility of the feedback system by incorporating additional functions into the PID algorithm. The low cost microcomputer expanded the potential for feedback control immensely, with algorithms limited only by the imagination of the programmer.

SCADAPack and TeleSAFE controllers employ a firmware PID algorithm that features the ease of use of the pneumatic controller, with the full control power of a computerized system. The controllers can service completely the control requirements of many industrial and bench scale applications. The PID control blocks are not limited to the PID control algorithm. They also provide ratio control, ratio/bias control, alarm scanning and square root functions. Control blocks may be interconnected to exchange setpoints, output limits, and other parameters.

PID control blocks operate independent of application programs. A elaborate control program need not be written to use the control blocks. A simple program to set up the control blocks is all that is required.

The main objectives of this manual are presenting how PID and ratio controllers are utilized in SCADAPack and TeleSAFE controllers, and guiding the user in their application. It is assumed that the reader already has an understanding of control theory. However, the rudiments of the PID algorithm are discussed to refresh the memories of experts and to introduce the concepts for those who are unfamiliar with the PID algorithm. Several rudimentary control schemes are discussed as well. Two techniques for tuning the PID controllers are presented. For experienced users, a section on implementing advanced control algorithms is included.

We have endeavored, as much as is possible, to present a clear, concise guide to the control blocks in controller. Everyone, including those familiar with other Control Microsystems products, should read this manual at least once, as concepts unique to the control blocks in the controller are discussed. New users are encouraged to read the manual twice, so that the more difficult concepts become clearer. A thorough study of the manual will enable you to extract the full potential of your controller.

# Introduction to PID Control

An automatic control system regulates a process by manipulating a control element through the feedback of a controlled output. The common household thermostat is an example of feedback control. The room temperature is compared to the temperature setting and a decision is made to turn the furnace on or off. The room temperature is known as the process value and the temperature setting is known as the setpoint. The furnace, in this case, is the control element.

A block diagram of a typical feedback control loop is shown in ***Figure 1***. The setpoint is fed into a comparator for comparison to the process value. For the household thermostat, the process value is the temperature of the house. The control algorithm makes the decision and generates the control output. The process is affected by the control output, resulting in a change in the process value. Ultimately, the process output will change sufficiently that the process value will approach the setpoint value.

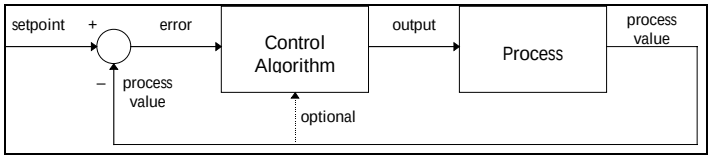



***Figure 1: Typical Feedback Control Loop***

Process control in the chemical processing industry has been used since the turn of the century, but efforts to understand feedback control were not extensive until the 1920's. The laying of the Trans-Atlantic communications cable necessitated the development of predictable and reliable transmission control. The foundations of modern control theory were set in this era.

The product of the original research in transmission control is the Proportional-Integral-Derivative (PID) controller that is now used extensively for industrial feedback control. In this chapter, the theory of the PID controller is explained. Rather than treating PID as a single entity, P, PI and PID controllers are discussed to illustrate the effect of each element. The development of the PID algorithm is explained step by step to provide a general understanding for the reader.

## Proportional Control

The proportional controller produces an output that is proportional to the difference between the setpoint and the process value. This difference is commonly referred to as the error. The greater the error, the greater the output of the controller. The equation for the output from a proportional controller is given as:

$$m = K \times e + m_s \qquad \text{Equation 1}$$

where: $m$ is the controller output
$K$ is the gain
$e$ is the error[1] = setpoint – process value
$m_s$ is a constant

[1] See the *Error* section on page **23** for a full description of how the error is calculated in the PID algorithm on the controller.

The error term is calculated as the difference of the setpoint and the process value. Thus, these two values must be measured in the same units.

*K* is the controller's proportional gain. It is the adjustable parameter in the controller that enables it to be tuned. By adjusting the gain, the magnitude of the control output can be changed for a given error. The parameter $m_s$ is equal to the steady state output required to produce an error of zero. When the error is zero, it can be seen from equation 1 that the controller output is necessarily equal to $m_s$. Thus, the steady-state error in a process controlled by a proportional controller is equal to zero if there are no changes in the process.

A problem arises with proportional control when a disturbance is introduced to the process. Disturbances result in a steady-state error ($e_{ss}$) as shown in ***Figure 2***. The best way to explain the effect of a disturbance is through the following example.

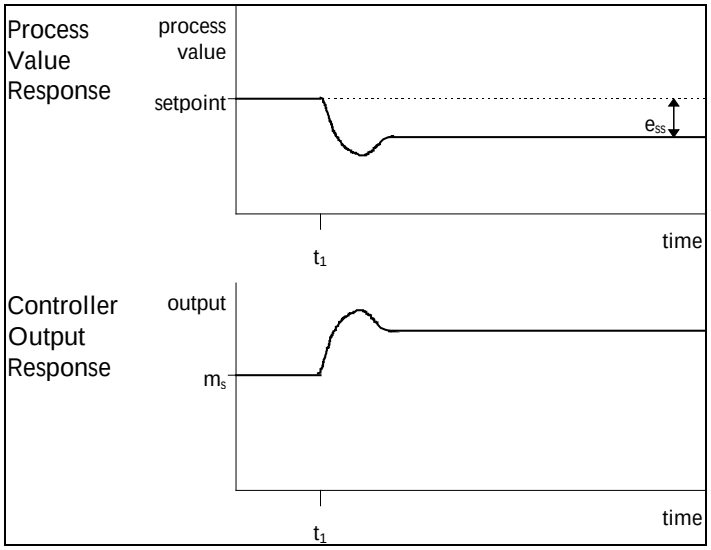



***Figure 2: Proportion Controller Response***

### *Example:*

A proportional controller is used to control the temperature of a house. The constant $m_s$ has been chosen so that the house temperature is 21°C. With this value of $m_s$ there is no error. Unfortunately, a window is left open on a winter day. The value of $m_s$ is insufficient to keep the temperature at 21°C resulting in an error. Since it is a proportional controller, the presence of an error causes the output of the controller to increase by the amount $K \times e$, but this increase is insufficient to raise the temperature of the house to the setpoint of 21°C. Thus, a steady-state error results.

***Figure 2*** shows the process value and the response of a P controller to a disturbance introduced at time $t_1$. At $t_1$, the process value is equal to the setpoint and the controller output is $m_s$. The disturbance causes the process value to fall below the setpoint. The resulting time varying error, causes the controller output to increase. This causes the error to decrease, but a steady-state error ($e_{ss}$) must persist in order to maintain the increased output of the controller.

Thus proportional controllers are very sensitive to disturbances, and given sufficient time and disturbances, a steady-state error will result.

## On/Off Control

A special case of the proportional controller is the On/Off controller (sometimes called a bang-bang controller). As the name implies, there are only two states of the output of an

on/off controller – on or off. There are no in-between states. The typical household thermostat is an example of this type of controller.

The equation for the on/off controller is:

$$m = K \times e, \quad K = \infty \qquad \text{Equation 2}$$

where: $m$ is the controller output
$K$ is the gain = ∞
$e$ is the error = setpoint – process value

This equation is similar to that of the proportional controller. The differences are that the gain is fixed at infinity, and the constant $m_s$ is removed (since the term $K \times e$ is so large, the term $m_s$ is essentially zero). Therefore, for any negative error (i.e. process value greater than setpoint) an infinitely negative output results; for any positive error, an infinitely positive output results.

In the case of the household thermostat, when the room is cold, the thermostat turns on the furnace and when it is warm, it turns off the furnace.

# Proportional-Integral Control

A proportional controller produces a steady-state error when a disturbance is introduced. This error can be eliminated by adding integral action to the P controller. This is known as proportional-integral (PI) control.

The equation for the output of a PI controller is:

$$m = K \times e + \frac{K}{T} \int e \, dt + m_s \qquad \text{Equation 3}$$

where: $m$ is the controller output
$K$ is the gain
$e$ is the error = setpoint – process value
$T$ is the reset time
$m_s$ is a constant
$\int e \, dt$ is the integration of all previous errors

The second term in the equation is known as the integral term. The other terms of the equation are unchanged from the P controller equation.

The parameter $T$ is an adjustable quantity that determines the amount of integral action in the output of the controller. The parameters $K$ and $T$ allow the PI controller to be tuned. It can be seen upon inspection of equation 3 that the PI controller becomes a P controller as $T$ approaches a positive infinite quantity ($T$ cannot be negative since it measures a time quantity). As $T$ approaches infinity, the integration term in the equation approaches zero.

The effect of adding integral action is to remove steady-state error. When an error exists, it is summed (integrated) with all the previous errors, thereby increasing or decreasing the output of the PI controller (depending upon whether the error is positive or negative). Thus, as the error accumulates in the integral term, the output changes so as to eliminate the error. A P controller will have a constant output when a steady-state error exists, thereby perpetuating the error. A PI controller reduces the steady-state error to zero, through the action of the integral term, as shown in ***Figure 3***.

### *Example:*

The temperature regulation of the house in the previous example can be improved by using a PI controller. If the window is opened on a cold day, a positive error results between the room temperature and the setpoint (i.e. the room is cold). The error accumulates in the integration term and as this term gets larger the output of the controller increases. As a result of the increase in the controller output, the room temperature increases until the setpoint is reached.

When the setpoint is reached, the error and all the subsequent errors are zero and the integration term becomes a constant. PI control has eliminated the steady-state error that results when a disturbance is encountered by a P controller.

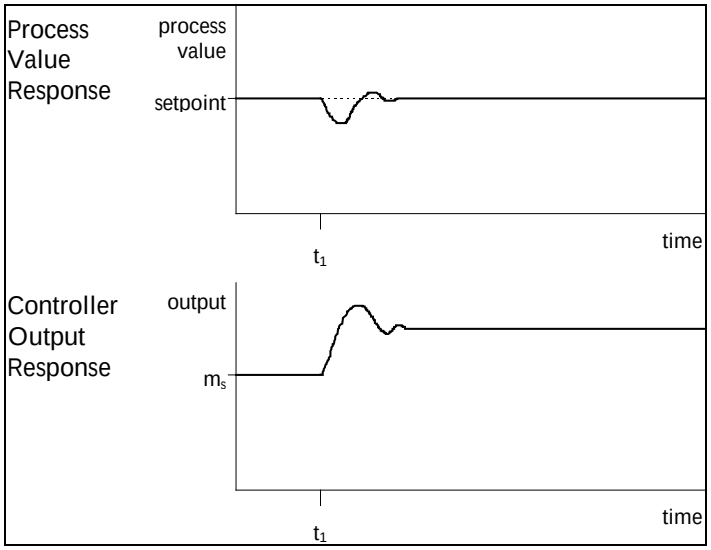



***Figure 3: Proportional-Integral Controller Response***

As a further illustration, assume that the window is now closed. Since a source of heat loss has been eliminated, the temperature rises above the 21°C setpoint producing negative errors. Summing these negative errors into the integral term decreases the output of the controller. The temperature then falls until the setpoint is reached, at which point the error and all subsequent errors are zero. When this occurs, the integral term ceases to decrease and becomes constant. The output of the controller is constant and the room temperature remains at the setpoint. Steady-state error has been avoided.

***Figure 3*** is representative of the typical response of the process and the PI controller to a disturbance. The steady-state error in ***Figure 2*** is not characteristic of the process response when regulated by a PI controller.

A novel (though not theoretically correct) way of viewing integral action is that it emulates the resetting of the setpoint. To see what is meant by this, consider that the occupant of the house in the previous example has found that the room temperature is below the desired level. The occupant is a P controller and regulates the temperature. Rather than checking for an open window, the occupant raises the thermostat setting every five minutes until the temperature is 21°C. The five minute period is the setpoint reset time, hence the naming of the parameter *T* in equation 3. It is important to understand that in a PI controller the setpoint is not altered. The integral term takes this "setpoint resetting" into account.

# Proportional-Integral-Derivative Control

The response of PI controller tends to be oscillatory. The process value continuously rises above and falls below the setpoint. This is the result of the integral action over-compensating for the error. The amplitude of the oscillations can be decreased by decreasing the proportional gain, *K*, or by decreasing the amount of integral action by increasing *T*. This results in a much slower response of the controller (i.e. a longer time to reach the setpoint once a disturbance has been introduced). The addition of derivative control to the PI controller improves the response of the controller when the gain and/or the integral action is decreased to eliminate the oscillatory response.

The equation for the PID controller is:

$$m = K \times e + \frac{K}{T} \int e\,dt + K \times R \times \frac{dp}{dt} + m_s \quad \text{Equation 4}$$

where: $m$ is the controller output
$K$ is the gain
$e$ is the error = setpoint – process value
$T$ is the reset time
$R$ is the rate gain
$p$ is the process value
$m_s$ is a constant
$\int e\,dt$ is the integration of all previous errors
$\frac{dp}{dt}$ is the rate of change of the process value

The third term in the equation is known as the derivative term, as it takes into consideration the rate of change of the process value. The other terms are unchanged from the PI controller.

The parameter *R* is the rate gain. The PID controller can be tuned to give an adequate response for any process, by adjusting the rate gain, along with the proportional gain and reset time. The derivative gain is adjusted to vary the magnitude of the output change for a given change in the process value. *R* is measured in time units; usually seconds.

Derivative (or anticipatory) action detects a change in the process value[2] and produces an output based upon the change. If the process value suddenly increases, the derivative action responds to decrease the output of the controller so as to decrease the process value. Derivative action anticipates a permanent increase or decrease in the process value, therefore improving the response of the controller by rapidly applying an opposing output.

***Figure 4*** illustrates the response of a PID controller to a disturbance introduced at time $t_1$. The response is quicker and less oscillatory than that of a PI controller. The peak in the controller response, known as the derivative peak, is caused by the sudden change in the process value.

Readers who have previously studied process control theory may have detected that the derivative term in equation 4 has been subtracted from the equation for the PI controller rather than added, as is stated in many process control textbooks. It also uses the rate of change of the process value rather than the rate of change of the error. Textbooks often state that these two rates are equivalent, but this is not necessarily true.

[2] Note that this is not necessarily the same as a change in the error.

To illustrate this point consider a process at steady-state. If the setpoint is changed there is an instantaneous and infinite rate of change in the error; but the rate of change of the process value is zero. Simply stated:

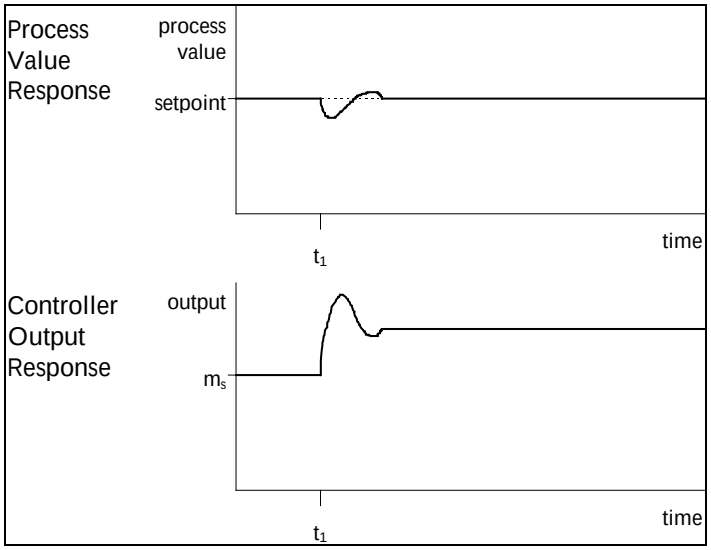



***Figure 4: Proportional-Integral-Derivative Response***

$$\frac{de}{dt} \neq \frac{dp}{dt}$$ Equation 5

during a setpoint change. As a result, the output of equation 4 is less sensitive to setpoint changes than the equation suggested by many textbooks. Also, equation 4 is much more sensitive to disturbances in the process, whereas the equation suggested in many textbooks can make the process unstable.

The Z-transform of equation 4 has been derived in Appendix A. A stability analysis on the PID controllers of SCADAPack and TeleSAFE controllers must be performed using this transfer function, rather than the ones cited in most textbooks.

# Cascade Control

Cascade controllers are often used when two control loops are interrelated. One of the two loops is usually fast acting, and the other slow acting with a long dead time. Usually, the slow acting controller is the primary controller and the fast acting controller is the secondary controller. Two examples of control situations applicable to cascade control are given below.

## Jacketed Vessel Control

Jacketed vessels (***Figure 5***) are often used to control the temperature of products. If the jacket volume is large relative to the tank volume, it may be very easy to overheat or overcool the jacket contents with the result that the temperature of the tank contents will cycle about the setpoint. Using one controller to maintain the jacket temperature with the setpoint of the controller determined by a second product temperature controller is an effective method to achieve accurate, high speed control.

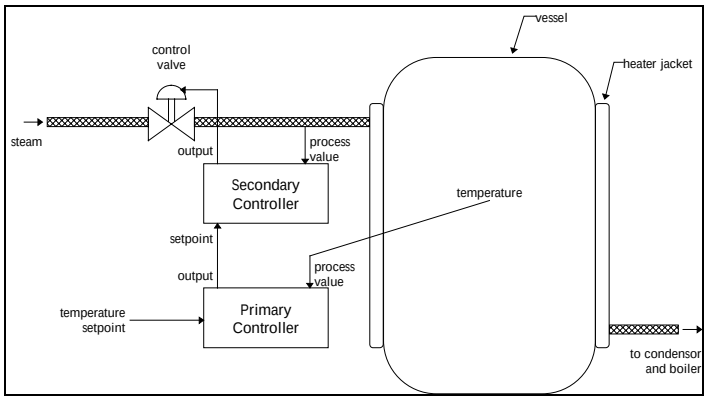



***Figure 5: Cascade Control of Jacketed Vessel***

## Ball Mill Control

Ball mills (***Figure 6***) operate best at specific ore loading levels. The loading level can be measured by the current required to rotate the mill. The motor current is the main controlling parameter and provides the input to the primary controller.

Weight belts with motor speed controls are often used to control the rate at which material is fed to the ball mill. The fast acting weigh belt signal forms the input to the secondary controller. The setpoint in the secondary controller is derived from the output of the primary ball mill motor current controller.

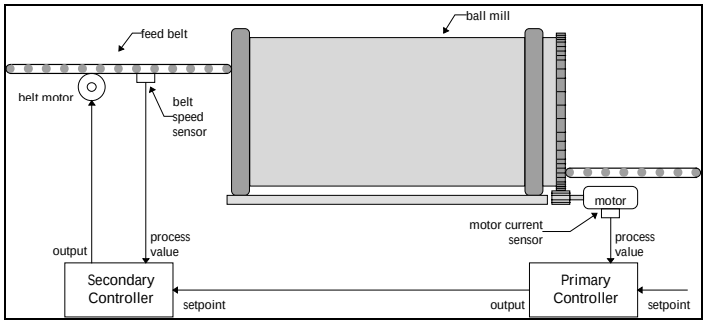



***Figure 6: Cascade Control of a Ball Mill***

# Ratio/Bias Control

A ratio/bias controller sets the controller output equal to the input multiplied by a constant, plus an optional output bias. Ratio controllers are used where an analog output must track an analog input or output signal.

Ratio/bias controllers can also be used to provide remote setpoint inputs for PID controllers. Refer to ***Remote Block Setpoints*** in the ***Control Block Setpoint Concepts*** section for a description of this capability.

The equation for the ratio/bias controller is:

$$m = K \times p + B_o \qquad \text{Equation 5}$$

where: $m$ is the controller output
$K$ is the ratio gain
$p$ is the process value
$B_o$ is the output bias

This equation is similar to that of the proportional controller. The difference is that it is the process value rather than the error (setpoint - process value) which is multiplied by the gain. The proportional controller will behave as a ratio controller if a negative gain and a setpoint of zero is used. However, for simplicity, the ratio controller has been incorporated as a separate entity in TelePACE PID control blocks.

Ratio/bias controllers are typically used to track the output of another controller. To illustrate this, consider the fuel flow rate to a furnace that is controlled by a PID controller. As more fuel is added, more air (in direct proportion) is required for combustion. A ratio controller whose input is the output of the fuel flow controller will add the required air in direct proportion.

# Time Proportioned Outputs

There are two possible types of output from a PID or ratio/bias controller: an analog signal and a time proportioned digital output (sometimes called a pulse duration output). An analog output sends the controller output quantity to an analog output module to generate an analog signal. A time proportioned output sends the controller output quantity indirectly to a digital output.

Simply stated, for a time proportioned output, the output of a PID controller is used to proportion a fixed time period into an "on-time" and an "off-time". During the on-time, a digital output is turned on; during the off-time the output is turned off.

The length of the on-time is proportional to the magnitude of the controller output, while the off-time is the difference between the fixed time period and the on-time. Consequently, the time proportioned output is a train of pulses of varying widths where the pulse width corresponds directly to the controller output.

In this way, the output simulates an analog output. ***Figure 7*** compares a time proportioned pulse train to an equivalent analog output. The width of the pulse is proportional to the height of the analog output at the start of each time period T.

The control elements that are best suited to time proportioned outputs are devices that can withstand frequent cycling between the on and off states. Such devices include solenoid valves controlling continuous flows, forward/reverse motor screws, high power electric heaters (where SCR controllers might be very expensive), and diaphragm valves with open/close control solenoids. Although it is possible to use electric motors with this type of output, excessive wear, caused by the frequent start-ups, may result.

There are operational limitations involved in using time proportioned control. Since a timer is used to set the on-time, the resolution of the pulse output is limited by the minimum time interval of the timer. The resolution can be improved by increasing the length of the fixed time interval that is being partitioned. The paradox here is that by increasing the fixed time period, the frequency of execution of the control algorithm is decreased, which can result in unstable response in extreme cases.

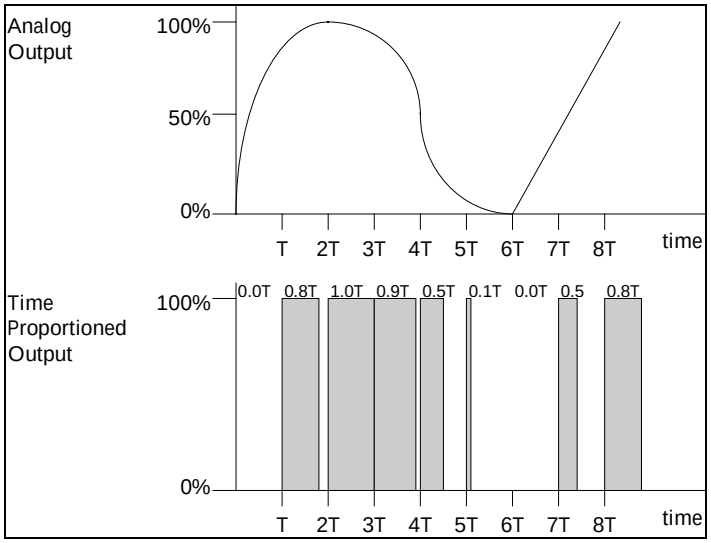



***Figure 7: Analog and Time Proportioned Outputs***

### *Example*

Consider that the temperature of a liquid in a vessel is regulated by a PID controller with a time proportioned output directed to a solenoid valve that admits steam to a jacket surrounding the vessel. The timer used to set the output on-time has a resolution of 0.1 second. The fixed time period is 10 seconds.

To illustrate the determination of the on-time consider that the PID controller has calculated an output of 30. The timer is thus loaded with 30 tenths of a second and since a non-zero on-time is required, the digital output to the solenoid valve is turned on.

After the timer has timed-out (after 3 seconds), the digital output is turned off for the remainder of the time period, that is 7 seconds. Once this period has passed, the control algorithm executes again and the cycle repeats.

# Square Root Linearization

PID controllers and ratio/bias controllers assume that the process value is linear. Some methods of measurement product non-linear signals. The output of the measurement device does not vary in a linear fashion with respect to the quantity being measured.

Consider the control of the flow rate of a liquid. The input to the controller is a height reading from a manometer (or more commonly a differential pressure cell) installed on the piping. It can be shown that the flow rate is proportional to the square root of the height of the manometer. The equation is:

$$f = K\sqrt{p + C}$$ Equation 6

where: $f$ is the flow rate
$K$ is the gain

*p* is the process value (reading from manometer)
*C* is a constant adjusting for pump head, NPSH and pipe friction

To use the manometer reading as a process value it must be linearized, by taking the square root, before the calculations of the PID controller or the ratio/bias controller can be performed. TelePACE PID controller blocks provide a square root extraction function for this purpose. If it is necessary to specify the constant C, the control blocks provide an input bias for this purpose.

An inherent problem with this linearization is that the precision of the process value is no longer linear over the range of the process value. The larger the process value, the more precise the result of the linearization.

## Square Root Normalization

The normal input range of the process value in TelePACE PID control blocks is –32767 to 32767 I/O counts. If square root extraction is performed on this range, a maximum value for the process value of 181 results. Since this effectively reduces the resolution (though not the precision) of the input, TelePACE PID control blocks normalize the square root value, by multiplying it by 128. Thus the square root of 32767 (181) becomes 23170.

The control blocks retain the sign of the value when a square root is extracted, and calculate the root on the magnitude of the value. This allows square root extraction on inputs whose values may be negative.

# Introduction to Control Blocks

TelePACE PID control blocks are capable of providing the following functions, or combinations of functions:

- P, PI, PID or PD control
- multi-loop cascade control
- on/off control
- ratio control
- ratio/bias control
- square root extraction
- alarm detection with annunciation

A control block may be configured to perform any of the above operations. Some configurations permit multiple functions within a block. For instance, only one block is required for a PID controller with square root extraction and alarm level detection on the process value. Other combinations are possible.

Blocks may be interconnected to combine their functions in a larger control scheme. For instance, multi-stream blending control can use one PID controller to control total stream flow with any number of slave ratio controllers to control the flow contributed by each stream. The same system could use other blocks to detect alarm levels on either controller outputs or stream flows; or to turn stream pumps on or off.

An important aspect of the control blocks is that they operate in the background, independent of application programs. However, application programs have full access to all block parameters and tuning parameters at any time. This permits advanced control concepts such as dynamic tuning. Programs written in C or Ladder Logic can supervise control loops to optimize their operation. In fact, application programs can even reconfigure the blocks during operation. For example, controllers can be set up to operate as proportional-only controllers when the error is large, and then be reconfigure to PI controllers when the error becomes smaller. This interaction between the program and the control blocks provides a very high degree of flexibility.

## Control Block Characteristics

The sections below describe the main features of the TelePACE PID control blocks.

### Background Operation

Control blocks operate in real time, separate from application programs. This ensures that time critical operations receive priority. Blocks can be set up to operate on individual time intervals. High speed control loops can be serviced more frequently than slower loops so as to distribute processor power where it is required. Control blocks will operate even when programs are being edited

## Independent Sample Times

Control blocks may be individually configured for ten executions per second to as few as one execution every 6553.5 seconds. Longer sample times consume fewer processor cycles, leaving more time available to application programs.

## Application Program Access

Application programs may read all control block tuning parameters and internal variables, even when the controllers are executing. Likewise, a program may store tuning parameters and internal variables into the controllers. This feature permits dynamic tuning of controllers during operation.

## Anti-Integral Windup

Anti-integral windup prevents integral summation (reset operation) if the outcome of such summation would be to set the controller output above or below the defined output limits.

## Output Limiting

Output limits may be programmed for each controller to prevent the controller from generating an output that is above or below desired limits.

## Square Root Extraction

Controllers may be configured to calculate the square root of the process value and/or the error. The sign (polarity) of the process value and/or error is retained. Square roots are useful when the process value is derived from orifice-plate flow meters or other devices which exhibit a square relationship.

## External Execution Inhibit

Each controller may use a digital input from the I/O system to prevent execution of the controller. The controller will halt execution as long as the input remains on.

## Automatic Alarm Scanning

A feature included in the control blocks (which is not related to the control algorithm) allows analog input channels to be monitored for levels above or below alarm limits, with a digital output turning on if an alarm condition exists. The digital address that turns on may be an interrupt input which will cause an immediate interrupt under alarm conditions.

## Deadband

A programmable deadband allows the PID controller algorithm to do a partial execution without changing the output if the absolute value of the error is less than or equal to the deadband. This partial execution is much faster than a full execution. It also prevents excess cycling of control elements, thereby reducing wear.

# Accessing Control Blocks

Each control block contains of a group of registers which define, tune and provide information about the block. Application programs access the control block through these registers. Additional functions control the execution of the blocks.

The following sections describe the access functions available in the C and Ladder Logic languages.

## C Language Functions

There are four library functions for accessing control blocks. Refer to the ***TelePACE C Tools*** manual for a complete description.

| Function | Description |
|---|---|
| set_pid | set a block variable to a specified value |
| get_pid | return the value of a block variable |
| auto_pid | set a block to execute automatically at the specified rate |
| clear_pid | set all block variables to zero |

The following C program shows a typical method of configuring a control block.

```
#include <ctools.h>

#define FLOW_CONTROLLER 0
#define FLOW_CONTROL_PERIOD   10

void configureFlowController( void )
{
   /* Clear control block variables */
   clear_pid(FLOW_CONTROLLER);

   /* Configure block characteristics */
   set_pid(CR, FLOW_CONTROLLER, PID_ANALOG_OP |
      PID_ANALOG_IP | PID_SP_NORMAL |
      PID_PID | PID_NO_ALARM | PID_NO_ER_SQR |
      PID_PV_SQR | PID_MODBUS_IO );
   set_pid(IP, FLOW_CONTROLLER, 30008);
   set_pid(IO, FLOW_CONTROLLER, 40014);
   set_pid(FS, FLOW_CONTROLLER, 32767);
   set_pid(ZE, FLOW_CONTROLLER, 0);

   /* Configure tuning parameters */
   set_pid(GA, FLOW_CONTROLlER, 340);
   set_pid(RE, FLOW_CONTROLLER, 470);
   set_pid(RA, FLOW_CONTROLLER, 0);

   set_pid(SP, FLOW_CONTROLLER, 2000);

   /* Execute block automatically */
   auto_pid(FLOW_CONTROLLER, FLOW_CONTROL_PERIOD);
}
```

### Setting Individual Bits

Sometimes it is desirable to turn on a bit or bits in the control or status registers without affecting any other bits. The OR operator is used to do this, as shown below.

```
int i;
i = get_pid( CR, x ) | 0x08;  /* set bit 3 */
set_pid( CR, x, i );       /* save new value */
```

### Clearing Individual Bits

Sometimes it is desirable to turn off a bit or bits in the control or status registers without affecting any other bits. The AND operator is used to do this, as shown below. The value used with the AND operator has all bits on, except the ones that are to be cleared.

```
int i;
i = get_pid( CR, x ) & 0xF8;  /* clear bits 0,1,2 */
set_pid( CR, x, i );       /* save new value */
```

## Ladder Logic Functions

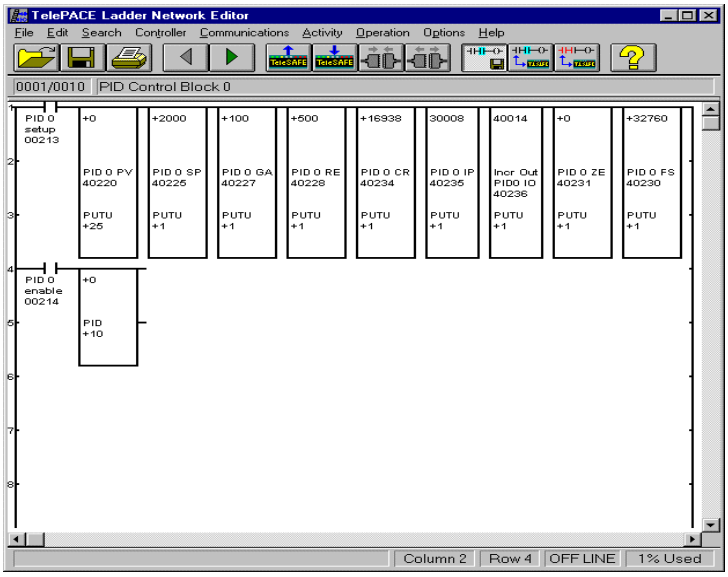
A ladder logic program accesses all control block variables through the I/O database. Refer to the I/O database documentation in the ***TelePACE Ladder Logic Editor*** manual for register addresses.

The **PUT** and **PUTU** functions are suitable for writing to the block variables. Both functions can write one value to a group of registers; this is useful for clearing a block prior to configuration.

The **PID** function controls execution of a block. The PID block starts execution on the rising edge on the input to the PID function and stops execution on the falling edge of the input to the PID function.

The following ladder logic program shows a typical method of configuring a control block. Note that the first **PUTU** function clears all variables in the block. The subsequent functions initialize the parameters.

The **pid 0 setup** and **pid 0 enable** contacts come from control logic elsewhere in the program. The setup contact is normally triggered by a one shot coil on the first execution of the program. The enable contact turns on when the PID controller is required.



# Control Block Variables

Control block variables are used to define and to tune the control blocks. Each block contains a set of variables. The following list shows the valid variable names, the range of valid values, and a brief description. A complete description of the variables follows.

| Variable | Range | Description |
|---|---|---|
| AO | 3 | alarm output address |
| CA | 3 | cascade setpoint source block number |
| CR | 3 | block control register |
| DB | 3 | deadband |
| DO | 3 | decrease output address |
| ER | 1 | PID error |
| FS | 1 | full scale output (high limit) |
| GA | 2 | gain |
| HI | 1 | high alarm level |
| IB | 1 | block input bias |
| IH | 3 | inhibit execution input address |
| IN | 2 | integrated error total |
| IO | 3 | increase output address |
| IP | 1 or 3 | block input source |
| LO | 1 | low alarm level |
| OB | 1 | block output bias |
| OP | 1 | block output quantity |
| PV | 1 | process value |
| RA | 1 | rate time (in 0.1 second increments) |
| RE | 1 | reset time (in 0.1 second increments) |
| SP | 1 | controller setpoint |
| SR | 1 | block status register |
| ZE | 1 | zero scale output (low limit) |

**Range 1** is an integer in the range –32768 to 32767.

**Range 2** is a fixed point integer with two fixed decimal places. The range is –32768 (=–327.68) to 32767 (=327.67).

**Range 3** is an integer in the range 0 to 65535.

The range does not indicate that any number that falls within it is suitable for the function of a controller. It only indicates the maximum and minimum values that can be used without generating an error and the accuracy of the representation.

For maximum execution speed, the control block algorithms operate on unscaled numeric quantities rather than engineering unit quantities. When a datum such as a setpoint is stored in a block, it must be stored in units that are acceptable to the algorithms. This usually means conversion from engineering units to 16 bit signed integer.

## Variable Descriptions

A description of the function and use of each block variable is given in this section. Not all variables are used with all configurations of a control block. The applicable block types are listed for each variable. The variables are listed in alphabetic order.

## Alarm Output Address - AO

Used with: alarms

The block alarm output address is a user defined variable which specifies the alarm output address. When a high or low alarm is detected, the digital output address specified in AO will be turned on if the block control register enables the alarms. For more information, see the ***Status Register*** section describing the alarm acknowledge bit of SR.

### Method One

If the I/O Specification bit in the control register is set to 1, AO may contain the address of any valid Modbus coil register. (e.g. 00014).

### Method Two

If the I/O Specification bit in the control register is cleared to 0, AO must contain an absolute address which is calculated as: channel * 8 + bit. Therefore to use channel 5, bit 3 as the alarm output, AO would be defined as 5 * 8 + 3 = 43. The absolute address method is only valid if the *Default* Register Assignment Table is downloaded to the controller, or if the controller is a TeleSAFE Micro16 with firmware version 1.22 or older.

## Cascaded Setpoint Source - CA

Used with: P, PI, PD, PID

The cascaded setpoint source block is a user defined variable in the control block that defines the source of cascaded setpoints for secondary cascaded controllers. It contains the block number whose output OP, will provide the setpoint for the PID controller. The output from the block specified in CA becomes the setpoint of the secondary cascaded controller.

The block cascade setpoint is only used by the control block when the block control register is configured as a P, PI, PID controller with setpoint from block CA.

## Control Register - CR

Used with: all

The block control register determines the function of the block. Refer to the ***Control Register*** section for a complete discussion.

## Deadband - DB

Used with: P, PI, PD, PID

The block deadband is a user defined variable in the control block that is used by the PID algorithm to determine if the process requires control outputs. If the absolute value of the block error is less than the block deadband, then the block skips execution of the control algorithm. This permits faster execution when the error is within a certain acceptable range or deadband.

To make the block perform a complete execution even on the smallest measurable error the block deadband should be set equal to 0.

To minimize background overhead, PID type blocks should use a reasonable value of deadband. Blocks execute up to five times faster if the error is within the deadband.

## Decrease Output - DO

Used with: P, PI, PD, PID, ratio, ratio/bias blocks with time proportioned outputs

The block decrease output address is a user defined variable in the control block that is used to define a pulse duration or motorized pulse duration output. When the block output, OP is negative, the digital output at DO is turned on for a length of time (in tenths of a second) equaling the absolute value of the block output. If the block output is positive, the digital output at DO is turned off.

### Method One

If the I/O Specification bit in the control register is set to 1, DO may contain the address of any valid Modbus coil register. (e.g.

### Method Two

If the I/O Specification bit in the control register is cleared to 0, DO must contain an absolute address which is calculated as: channel * 8 + bit. For example, bit 7 of channel 13 will equal 13 * 8 + 7 = 111. The absolute address method is only valid if the *Default* Register Assignment Table is downloaded to the controller, or if the controller is a TeleSAFE Micro16 with firmware version 1.22 or older.

## Error - ER

Used with: P, PI, PD, PID

The block error is a variable generated by the control block that contains the process error from the most recent calculation. The initial calculation is

ER = SP – PV

If the absolute value of the error is less than the deadband, no further calculation is done and the output of the block does not change.

If the absolute value of the error is equal to or greater than the deadband, then the error is calculated using the formulae below.

ER = SP – PV + DB if the PV is greater than setpoint

ER = SP – PV – DB if the PV is less than the setpoint

This calculation ensures there is no large jump in the error, and a corresponding process disturbance when the process comes out of the deadband.

## Full Scale Output - FS

Used with: P, PI, PD, PID, ratio, ratio/bias

The block full scale output is a user defined variable in the control block used in limiting the maximum block output. If the control block calculates a block output quantity that is greater than the value stored in FS, the block output quantity OP is set equal to the value stored in FS.

The units of the block full scale output vary depending whether the control block is time proportioned or analog output. For time proportioned outputs, the units are tenths of seconds and the value is usually set equal to or less than the block execution time. For analog outputs, the integer is stored in I/O units (-32767 to 32767). The block full scale output should always be greater than the block zero scale output.

## Gain - GA

Used with: P, PI, PD, PID, ratio, ratio/bias

Gain is a user defined variable in the control block. It is the proportional gain if the block control register is configured as a P, PI, PD, or PID controller. It is the ratio if the block control register is configured as a ratio or ratio/bias controller.

The value stored in the gain is a 2 decimal place fixed point integer. Since there is no actual decimal point, the value stored in the gain is 100 times the actual gain. For example a gain of 1.50 is stored as 150.

A positive value of gain configures a forward-acting PID controller and a negative value of gain configures a reverse acting controller.

## High Alarm Level - HI

Used with: alarms

The block high alarm level is a user defined variable in the control block that indicates at what value the high alarm is triggered. If the block process value PV exceeds or equals the value stored in HI then the digital output specified in AO is turned on.

The block high alarm level is normally specified in the units of the process value PV. The alarm will only be announced if the block control register is configured for alarms active.

If neither a low alarm nor a high alarm exists, the output specified in AO will be turned off.

## Input Bias - IB

Used with: P, PI, PD, PID, alarms, ratio, ratio/bias

The block input bias is a user defined variable in the control block that is used by either the PID or the ratio/bias algorithm to cancel true-zero offset in the input signal to the control block. The value stored in IB is subtracted from the block input before any of the block algorithms execute. The quantity stored in PV already has the input bias subtracted.

The block input bias is usually expressed in the units of the process value PV.

Block input bias can be useful in calibrating input signal sources by storing the actual instrument reading into the input bias under conditions of known true zero process signals.

## Inhibit Execution Input - IH

Used with: all

The block inhibit execution input address is a user defined variable in the control block which specifies a digital input bit. It is used to disable or enable the automatic execution of a control block depending upon whether a control bit is on or off. A value of zero stored in IH disables this function.

The block will be prevented from executing whenever the bit whose address is stored in IH is on. When the bit turns off, execution will resume, but the resumption will not be bumpless. If the block input changes during the period execution is inhibited, the change will immediately appear at the block output on resumption of execution.

### Method One

If the I/O Specification bit in the control register is set to 1, IH may contain the address of any valid Modbus status register (e.g. 10023).

### Method Two

If the I/O Specification bit in the control register is cleared to 0, IH must contain an absolute address (i.e. channel * 8 + bit). Channel 0, bit 0 cannot be used as a valid absolute address

for IH. The absolute address method is only valid if the *Default* Register Assignment Table is downloaded to the controller, or if the controller is a TeleSAFE Micro16 with firmware version 1.22 or older.

## Integrated Error - IN

Used with: PI, PID

The block integrated error is a variable generated by the control block if it is configured as a PI or PID controller. The value stored in the integrated error is a 2 decimal place fixed point integer. Since there is no actual decimal point, the value stored is 100 times the actual error. For example an integrated error of 71.02 would be stored as 7102.

Changes to IN will not occur under the following conditions:

- Block output tries to exceed FS
- Block output tries to drop below ZE
- Block reset time is equal to zero
- Block inhibit execution input is ON
- The block integral is greater than 32767
- The block integral is less than –32768.

The first two conditions are known as integral anti-windup. The integrated error in a control block can be set to zero by storing 0 in the IN register.

## Increase Output - IO

Used with: P, PI, PD, PID, ratio, ratio/bias blocks with analog or time proportioned outputs

The block increase output address is a user defined variable in the control block that is used to define a block output point as follows:

### Method One

If the I/O Specification bit in the control register is set to 1.

| Output Type | Function of IO |
|---|---|
| Analog | IO contains a valid Modbus holding register. |
| time proportioned | IO contains a valid Modbus coil register. When the block output, OP is positive, the digital output at IO is turned on for a length of time (in tenths of a second) equaling the block output. If the block output is negative, the digital output at IO is turned off. |

### Method Two

If the I/O Specification bit in the control register is cleared to 0. This address method is only valid if the *Default* Register Assignment Table is downloaded to the controller, or if the controller is a TeleSAFE Micro16 with firmware version 1.22 or older. This is included to provide backward compatibility for older controller.

| Output Type | Function of IO |
|---|---|
| Analog | IO contains the analog channel number. |
| time proportioned | IO contains an absolute digital address calculated as channel * 8 + bit. |

## Input Source - IP

Used with: all

The block input source is a user defined variable in the control block that is used by the control block to determine the source of the process value. The process value for the control block is taken from the source specified in IP.

The value in IP is dependent upon the configuration of the block input in the control register (see the ***Control Register*** section).

### Method One

If the I/O Specification bit in the control register is set to 1.

| Block Input | Function of IP |
|---|---|
| None | IP contains the process value. This is useful in running simulations. |
| analog | IP contains the Modbus input or holding register from which the process value is expected. This is the most often used configuration of a PID controller's process value. |
| block output | IP contains the control block number from whose output the process value is taken. |

### Method Two

If the I/O Specification bit in the control register is cleared to 0. This address method is only valid if the *Default* Register Assignment Table is downloaded to the controller, or if the controller is a TeleSAFE Micro16 with firmware version 1.22 or older. This is included to provide backward compatibility for older controller.

| Block Input | Function of IP |
|---|---|
| none | IP contains the process value. This is useful in running simulations. |
| analog | IP contains the analog channel from which the process value is expected. This is the most often used configuration of a PID controller's process value. |
| block output | IP contains the control block number from whose output the process value is taken. |

## Low Alarm Level - LO

Used with: auto alarms

The block low alarm level is a user defined variable in the control block that indicates at what value the low alarm is triggered. If the block process value PV is less than or equal to the value stored in LO then the digital output specified in AO is turned on.

The block high alarm level is normally specified in the units of the process value PV. The alarm will only be announced if the block control register is configured for alarms active.

If neither a low alarm nor a high alarm exists, the output specified in AO will be turned off.

## Output Bias - OB

Used with: P, PI, PD, PID, ratio, ratio/bias

The block output bias is a user defined variable in the control block that is used by either the PID or the ratio/bias algorithm in calculating the output quantity. The output bias is added to the output of the control algorithm and can be used to shift the output up or down the scale.

Output bias is useful with 4-20 mA outputs. With an analog output module that generates 0-20 mA, an output bias of 6553 will ensure a 4 mA output when the algorithm output equals 0. With an analog output module that generates 4-20 mA, an output bias of 0 should be used.

## Output Quantity - OP

Used with: P, PI, PD, PID, ratio, ratio/bias

The block output quantity is a variable generated by the control block that contains the algorithm output after the addition of output bias. It is a full range integer (–32768 to 32767) but is limited by the quantities stored in the zero scale ZE and the full scale FS.

## Process Value - PV

Used with: all

The block process value is a variable generated by the control block that contains the block input (process value) which existed at the most recent execution of the algorithm. The block input can come from an analog channel, another block's output, or a constant generated by a program, as defined by the block control register and IP.

## Rate Time - RA

Used with: PD, PID

The block rate time is a user defined variable in the control block that controls the rate gain (or magnitude of derivative action) in a PD or PID controller. The possible range of values is 0 to 32767. The PID algorithm assumes that the rate time is stored in units of tenths of a second.

If RA = 0, no rate (or derivative) action will be used in the block. Maximum rate action occurs when RA = 32767. Minimum rate action occurs when RA = 1. To make a controller P or PI type, RA should equal 0.

## Reset Time - RE

Used with: PI, PID

The block reset time is a user defined variable in the control block that controls the reset gain (or magnitude of integral action) in a PI or PID controller. The possible range of values is 0 to 32767. The PID algorithm assumes that the reset time stored in RE is in units of tenths of a second.

If RE = 0, no reset (or integral) action will be used in the block. Maximum reset action occurs when RE = 1. Minimum reset action occurs when RE = 32767. For P or PD controllers, RE should equal 0.

## Setpoint - SP

Used with: P, PI, PD, PID

The block setpoint is a user defined variable in the control block that is used to calculate the error in the PID algorithm. It is a dimension-less 16-bit signed integer (–32767 to 32767).

If the block has a cascaded setpoint, then SP is not user definable, but will be defined by the block and will equal the value of the cascaded setpoint. SP always contains the setpoint which is used by the block algorithm, regardless whether it is user defined or cascaded.

## Status Register - SR

Used with: all

The block status register reports the status of conditions affecting the block. Refer to the ***Status Register*** section for a complete discussion.

## Zero Scale Output - ZE

Used with: P, PI, PD, PID, ratio, ratio/bias

The block zero scale output is a user defined variable in the control block used in limiting the minimum block output quantity. If the control block calculates a block output quantity that is less than the value stored in ZE, the block output quantity OP is set equal to the value stored in ZE.

The units of the block zero scale output vary depending whether the control block is time proportioned or analog output. For time proportioned outputs, the units are tenths of seconds and the value is usually set equal to the negative block execution time (i.e. time x –1). For analog outputs, the value is stored in I/O counts. The block zero scale output should always be less than the block full scale output.

# Control Block Input Concepts

All control blocks require an input. This input can be an output of another control block, an analog signal from a process sensor, or a constant. The block variable IP specifies the input source, according to the type of input defined by the block control register (see the ***Control Register*** section).

- If the input is a constant, the constant is directly stored in IP.
- If the input is an analog signal, the address of the Modbus input register is stored in IP.
- If the input is taken from the output of another control block, the block number is stored in IP.

Input limits for constants and analog signals –32767 to 32767. A block input derived from the output of another block is limited by the output range limits ZE and FS of the block supplying the output.

## Constant Block Inputs

A constant block input is generated by a application program. Constant block inputs are defined by setting bits 2 and 3 of the block control register to zero. The input value is specified by storing the value in the IP register.

Process simulation and special input signal conditioning are the usual applications for constant inputs.

### Process Simulation

A model of a process can be derived and programmed. The model supplies all block inputs to the control blocks by declaring IP = model output. Inputs to the model are derived from control block outputs, OP.

### Signal Conditioning

Input signal conditioning is often used where the instrumentation signal source has a non-linear relationship, other than a square root relationship, to the real process value. It can also be used to average several analog input readings, or to provide filtering of the raw process value in noisy environments.

#### *Example*

The process value for block 8 is to be obtained from the average of the three analog inputs at registers 30001, 30002 and 30003. This application might be useful in the temperature control of a large vessel, where multiple temperature probes are used.

In a C application program the following statement is used.

```
set_pid( IP, 8,
(dbase(30001)+dbase(30002)+dbase(30003))/3);
```

## Analog Block Inputs

An analog block input is read from an analog I/O channel. The block variable IP holds the Modbus address of the analog channel. The channel may be either an input channel or an output channel. To enable analog channel block inputs, bit 2 of the control register CR should

be 0 while bit 3 should be 1. The analog channel will be read each time the block algorithm executes.

### Input Channel Block Inputs

Block inputs from analog inputs are most commonly used with feedback control. The process signal is obtained from an instrument such as a temperature transmitter whose output is connected to an analog input module.

Another common application for analog block inputs is in the generation of remote setpoints. In this application a ratio/bias block reads the analog input channel where the remote setpoint is connected. The ratio block output is usually configured as an internal output where it can be cascaded into the setpoint of the other controller.

### Output Channel Block Inputs

Block inputs from analog outputs are most commonly used with ratio/bias blocks. For example, a fuel/air ratio control system could use a PID controller to regulate the fuel flow with a 4-20 mA control valve. A ratio controller can get its input from the PID controller analog output. The ratio block output could drive air control dampers (open loop), or could provide the cascaded setpoint for a PID controller on the air control system (closed loop).

## Block Output Block Inputs

Block output block inputs is a confusing name for a simple concept. A control block can receive it's input directly from the output of another block. This is used most commonly with ratio/bias controllers. Applications include blending control, and output tracking.

### Stream Blending Control

In a typical multiple stream blending control system, one PID controller monitors the total stream flow. The output of this controller can be read by any number of ratio/bias blocks to obtain the flow setpoint for each of the individual streams. The example for ***Batch Control*** describes the configuration of a complex multiple stream blending control system.

### Output Tracking

In a previous example we described a fuel/air control system wherein the air flow setpoint is derived from the fuel flow analog output. Another way of obtaining the same function is to have the air controller read the output of the fuel controller directly; not the fuel control analog output. This configuration is somewhat faster since blocks can get their inputs faster from block outputs than from analog channels.

# Control Block Output Concepts

At the conclusion of execution, the control block algorithm generates a numeric quantity that is stored in the block variable OP. This quantity is the block output. The block output can be directed to one of several destinations, depending upon the requirements of the control algorithm. Limits may also be applied to the output value.

## Block Output Types

A control block always store it's output in the block variable OP. This value may be accessed by an application program, or by a control block for a cascaded setpoint. The output can also be directed to analog outputs, time proportioned outputs or dummy analog outputs.

### Analog Outputs

The output of the controller is sent to an analog output channel. This output is commonly used with 4-20 mA control valves and 0-10V recorders.

### Time Proportioned Outputs

A block output may be used to control a on/off control elements with a time proportioned output (also known as a pulse duration output). The value of OP determines the length of time a digital output will be turned on. The output is turned off for the remainder of the execution period.

Two types of time proportioned outputs are available; pulse duration and motor pulse duration. Pulse duration outputs are used with elements such as solenoid values, motors and electric heaters that must be cycled to maintain a setpoint. Motor pulse duration outputs are used with motors that must be shut off when a setpoint is reached, such as a positioning motor. The differences in operation are explained below.

A control block with time proportioned outputs operates identically to an analog output or cascade output controller up until the point where the output has been calculated. At this point, the algorithm performs one of four actions:

1. If the control block type is motor pulse duration and the error is within the deadband, both the DO and IO outputs are turned off. The control block timer is set to zero.
2. If the output is zero, both the DO and IO outputs are turned off. The control block timer is set to zero.
3. If the output is negative, the DO output is turned on, the IO output is turned off, and the absolute value of the controller output quantity is will be loaded into a timer. When the timer reaches zero, the DO output is turned off.
4. If the output is positive, the IO output is turned on, the DO output is turned off, and the absolute value of the controller output quantity is will be loaded into a timer. When the timer reaches zero, the IO output is turned off.

The output on-time period is equal to the controller output quantity and is measured in tenths of a second.

## Choosing the Execution Period

Several factors influence the choice of the execution period of a control block with a time proportioned output. There must exist a good compromise between execution period, controller gain and controller output.

- Control blocks will update the outputs and reload the timer only after each execution of the controller.
- If the output quantity is larger than the execution time, the output will remain on constantly.
- The longer the execution period, the greater the resolution of the output. For instance, if the controller executes once every ten seconds, with an interval time of one tenth of a second, it will yield a resolution of one part in one hundred (1%).
- If the execution period is too long relative to the process response time, the process value may under/over shoot.

The choice of an execution period depends on the process under control. The following procedure will aid you in determining the period.

1. Declare high and low output limits equal to the execution period. This will prevent the output from turning on for a time period greater than the loop update time. For instance, with an execution time of ten seconds set the full scale output FS to 100, and the zero scale output ZE equal to –100.
2. Experiment with the process to determine at what process value the outputs should begin cycling on/off. For example in a heating system, it may be determined that from the time the heat is turned off, the process temperature will increase three more degrees over a period of several minutes. This would indicate that the heat should start cycling when the process value is somewhat greater than three degrees below the setpoint. Assume that six degrees will be adequate.
3. Convert the process units into I/O units. For example consider a 4-20 mA input with a 0-100 degree calibration. Each degree will equal 262.136 counts in I/O quantities. Six degrees will yield 1573 counts.
4. Determine the maximum loop update time taking into consideration process response time and desired output resolution. Assume in our example that a ten second execution update time is adequate.
5. Calculate the PID gain to yield an output time period equal to the loop update period at the error at which the output should begin cycling. In our example, the gain should equal approximately 100 tenths of a second update divided by 1573 counts for 0.06. Calculating the gain thus ensures that the output will begin cycling at the determined temperature. The gain can then be adjusted to yield the best performance.
6. When determining the gain estimate, err on the low side. This will result in the output cycling too early. Gains on time proportioned output controllers will usually have low values.
7. Do not use an output bias. Bias should be declared equal to zero.
8. Keep the execution period as long as possible for maximum output resolution.

## Single Acting Control

A time proportioned output controller activates either the DO or the IO output depending on the controller output polarity. If the output limits as determined by ZE and FS are appropriately programmed, either output can be prevented from turning on.

The controller can be configured for single acting control in either direction. Referring to our previous example of heating control, the loop can be configured to cool only, or heat only. To

define a controller in which only the IO output will turn on, the output limit ZE should be programmed at zero. Preventing the output from going negative ensures that the DO output will never turn on.

### Dual Acting Control With 2 Controllers

Sometimes, dual acting control elements exhibit significantly different response characteristics. A dual acting controller can be optimized for each control element by using two, single acting time proportioned output controllers which are individually tuned. The controllers will be tuned in the normal fashion but the following points should be noted:

- Both blocks should have the same setpoint so that they do not activate the control elements in opposition.
- Both blocks should use a deadband to minimize the probability of output opposition due to different reset action.
- Both blocks should use the other's output as an inhibit execution input. This will prevent the block from executing (and maybe turning on its output) if the other block's output is on.

## Dummy Analog Outputs

A dummy analog output is a Modbus holding register which has not been assigned to an output module. Such a register is also called a general purpose holding register. The output of the block is stored in the holding register where it can be accessed by other blocks or application programs. Dummy analog outputs are configured in exactly the same fashion as true analog outputs.

# Output Limiting

The range of the block output is defined by the full and zero scale output limits. The limits allow the user to restrict the range of analog outputs, cascade setpoints, and the maximum and minimum on-time of time proportioned outputs. This is useful when the full range of operation of control devices could result in damage to the process or excess product being produced.

## Zero Scale Output Limit

The zero scale (or minimum) output limit is determined by the quantity which is stored in the block variable ZE. The block output is allowed to go as low as the quantity stored in ZE, but no lower. A negative quantity is permitted in some circumstances as explained below. The zero scale limit should always be less than the full scale limit, or indeterminate operation will result.

## Full Scale Output Limit

The full scale (or maximum) output limit is determined by the quantity which is stored in the block variable FS. The block output is allowed to rise up to and equal the value stored in FS, but not to exceed it. The full scale limit should always be greater than the zero scale limit value, or indeterminate operation will result.

## Analog Block Output Limits

Analog output limits prevent the output signal from exceeding pre-defined limits. This is particularly useful with 4-20 mA analog outputs. The I/O system is capable of generating 0-20

mA outputs. By setting the zero scale limit to 6553, the output is prevented from dropping below 4 mA. The quantity 6553 is obtained by scaling the 0 to 32767 I/O count output to mA:

$$ZE = \frac{4mA}{20mA} \times 32767 = 6553$$

The analog output system uses 16-bit signed numbers; thus the analog output range is 0 to 32767. The I/O system only permits positive polarity analog outputs. If ZE is less than 0 the output will be clamped at 0. If FS is greater than 32767, the output will be clamped to 32767.

## Time Proportioned Output Limits

The block output value determines two factors for time proportioned outputs: which of the increase or decrease outputs is turned on; and the time period for which it is turned on. If the block output is negative, the decrease output, DO, will turn on and the increase output, IO, will turn off. If the block output is positive, the increase output, IO, will turn on and the decrease output, DO, will turn off. If the output is zero, both outputs will be turned off. Dual outputs such as this are usually referred to as double acting.

The output limits can be used to prevent one of the outputs from turning on, thereby providing the controller with a single acting output. If ZE is set to zero, output DO cannot turn on as the block output will never be negative.

The output limits can also be used to limit the on-time of an output. The on-time is equal to the block output value. ZE and FS set the maximum value of this time period, for decrease outputs and increase outputs respectively. The block output limits should be set equal to the execution period of the block if no limiting is desired.

See the ***Time Proportioned Outputs*** section above for more information.

## Dummy Analog Output Limits

Dummy analog channel block outputs behave identically to standard analog outputs. Since the I/O system does not permit bipolar analog outputs, the block output is restricted to the range 0 to 32767. Setting the zero scale limit to a negative quantity will have no effect; the minimum output will be clamped at zero.

## Internal Block Output Limits

An internal block output may be bipolar. The zero scale limit may therefore be set to a negative value.

# Control Block Setpoint Concepts

The block setpoint is the desired value of the process value. The source of the setpoint, SP can be a constant or the output of another control block (cascaded setpoint). Setpoints can also be obtained from a remote source through an analog input or ramped by an application program.

## Constant Setpoints

A constant setpoint is generally set by an operator, although it can be generated by an application program. It is stored in the SP register by an application program, or through the I/O database. A constant setpoint is configured by clearing bit 4 of the block control register (CR).

C application programs store the setpoint with the **set_pid** function or by writing to the I/O database with the **setdbase** function.

Ladder logic programs store the setpoint with a **PUT**, **PUTU**, or other register transfer function.

A host computer stores a setpoint by writing to the appropriate register in the I/O database. Refer to the C or ladder logic user manual for details on the I/O database.

## Cascaded Setpoints

A cascaded setpoint comes from the output of another control block. The source is set by storing the block number of the primary block in the CA register. A constant setpoint is configured by clearing bit 4 of the block control register (CR) in the secondary (destination) control block.

***Example:***

Control block 1 is used as the primary controller and control block 2 is used as the secondary controller in a cascade configuration. The value stored in CA of block 2 is 1 and bit 4 of this control register must be set. Once both control blocks are in operation the setpoint of block 2 will be equal to the output of block 1.

## Remote Block Setpoints

Remote setpoint controllers derive their setpoint from an external device rather than direct programming or cascade control. For instance, a potentiometer may be the best method of allowing an operator to change the setpoint. Or, a high speed hardware controller may pass it's output into the setpoint of a TelePACE PID control block. The latter is an example of cascade control where the primary controller is external hardware and the secondary control is provided by the controller.

Remote setpoints are best implemented using the following technique:

- Define a ratio/bias controller to read the analog input.
- Cascade the output of the ratio/bias controller into the setpoint of a second control block.
- Both controllers must have the same execution period (see the ***Control Block Execution*** section).

The advantages of using a ratio/bias controller are many. The setpoint updates automatically, without intervention by an application program. All features provided by ratio/bias controllers can be applied to remote setpoints. These include: square root extraction, output limiting, alarm detection, remote setpoint bias, and non-direct ratios (other than 1:1).

### *Example:*

PID controller 11 is to obtain its setpoint from analog input register 30008. The analog input is a 4-20 mA signal. Block 5 will be used as the ratio controller.

1. Configure control block 11 with appropriate parameters for gain, reset time, deadband, output bias, etc.
2. Set the CA register of block 11 to 5.
3. Set bit 4 of the control register of block 11 to select a cascaded setpoint.
4. Configure control block 5 as a ratio/bias controller with internal output with the following parameters:

| Parameter | Register | Value | Comments |
|---|---|---|---|
| Gain | GA | 1 | 1:1 ratio |
| output bias | OB | 0 | Not required |
| zero scale output | ZE | 6553 | Ensure output is > 4 mA |
| full scale output | FS | 32767 | Full 20 mA output allowed |
| input source | IP | 30008 | Analog input register |
| control register | CR | 8+<br>64+<br>16384<br>=16456 | Analog input<br>ratio/bias<br>Modbus I/O |

Both controllers must have the same execution period.

## Ramping Setpoints

Setpoints can be ramped from one value to another using an application program or another control block. An application program can use several methods for ramping a setpoint. A simple technique is to increase or decrease the setpoint in a loop with a delay to control the ramping rate. A timer can also be used to regulate the ramp rate.

# Control Register

The block control register is a special block variable which determines which functions are engaged in a control block. The block control register is a 16-bit quantity with each bit undertaking special significance. The table below lists the functions of the control register bits.

| Function | Bits | Value | Options |
|---|---|---|---|
| Block Output | 0,1 | 0<br>1<br>2<br>3 | 00 – none other than OP<br>01 – pulse duration<br>10 – analog channel<br>11 – motor pulse duration |
| Block Input | 2,3 | 0<br>4<br>8<br>12 | 00 – none (comes from IP)<br>01 – from output of block IP<br>10 – analog channel<br>11 – undefined |
| Setpoint Source | 4 | 0<br>16 | 0 – setpoint is stored in SP<br>1 – from output of block CA |
| Block Function | 5,6 | 0<br>32<br>64<br>96 | 00 – alarm only<br>01 – P, PI, PD or PID controller<br>10 – ratio or ratio/bias controller<br>11 – undefined |
| Alarm Status | 7 | 0<br>128 | 0 – not enabled<br>1 – alarms active |
| Square Root of Error | 8 | 0<br>256 | 0 – not enabled<br>1 – take square root of error |
| Square Root of PV Input | 9 | 0<br>512 | 0 – not enabled<br>1 – take square root of PV input |
| Alarm Type | 10,11 | 0<br>1024<br>2048<br>3072 | 00 – absolute level<br>01 – deviation from setpoint<br>10 – rate of change<br>11 – undefined |
| Setpoint Tracking | 12 | 0<br>4096 | 0 – not enabled<br>1 – SP tracks PV in manual mode |
| Manual Mode | 13 | 0<br>8192 | 0 – non manual mode<br>1 – manual mode |
| I/O Specification | 14 | 0<br><br>16384 | 0 – absolute addresses specified from fixed I/O map.<br>1 – Modbus registers specified |
| unused | 15 | | |

The controller configuration bits should not be changed while the controller is in operation. The only exceptions are the alarm status and manual mode bits. The recommended technique is:

- turn off the controller;
- reconfigure the control register and other variables as required; and
- re-enable the controller.

To enable a function, the corresponding bit in the control register must be set to 1. To disable any of the above functions, the corresponding bit in the control register must be cleared to 0. The simplest method of selecting the proper bits is to add their values shown in the table.

### *Example*

A controller block is to have the following functions enabled: PID controller, analog input, pulse duration output, square root of process value, normal setpoint, alarms engaged, and Modbus I/O specification. The values of the functions are listed below. The value of the control register is the sum of the function values.

| Function | Value |
|---|---|
| PID | 32 |
| Analog Input | 8 |
| Pulse Duration Output | 1 |
| Square Root of PV Input | 512 |
| Alarms Enabled | 128 |
| Modbus I/O Specification | 16384 |
| Value of CR register | 17065 |

# Block Alarms

The control blocks provide automatic alarm detection. The alarms may be detected on the basis of the absolute process value level, the deviation of the process value from the setpoint, or the rate of change of the process value.

There are three bits in the control register which control the block alarms. Bit 7 enables the alarms. Bits 10 and 11 specify the type of alarms.

There are two alarm setpoints for each block, specified by HI and LO. An application program can determine which alarm occurred from the alarm bits in the block status register.

## Absolute Level Alarm

Absolute level alarms compare the process value (PV) to the alarm setpoints. An alarm is detected when:

- the process value is greater than or equal to the high alarm setpoint (HI); or
- the process value is less than or equal to the low alarm setpoint (LO).

## Deviation Alarm

The deviation from setpoint alarm compares the controller error (ER) to the alarm setpoints. An alarm is detected when:

- the controller error ER is equal to or greater than the high alarm setpoint (HI); or
- the controller error ER is equal to or less than the low alarm setpoint (LO).

## Rate Of Change Alarm

The rate of change alarm compares the difference between the current process value (PV) and the process value the last time the loop was executed, to the alarm setpoints. An alarm is detected when:

- the change in process value is greater than or equal to the high alarm setpoint (HI); or

- the change in process value is less than or equal to the negative value contained in the low alarm setpoint (LO).

The low alarm setpoint specifies what decrease in the process value (during one block execution period) will result in an alarm. The low alarm setpoint must be negative. For example, if the current process value is 2000 and the previous value was 2025, then the change is 2000–2025 = –25. An alarm will be detected if the low alarm level is in the range –1 to –25.

# Manual Mode

The block manual mode suspends operation of the automatic control algorithm (PID or ratio/bias), but continues operation of other block functions. Manual mode should not be confused with the inhibit execution input function which stops all block functions.

While in manual mode, the process value (PV) is refreshed (upon each block execution) from the previously specified block input source IP. The block output, OP, is maintained at the last value it had before the switch to manual mode. An application program vary the OP register if desired. If time proportioned output is being used, the duty cycle is maintained while in manual mode; and is adjusted for changes in the OP value.

Manual mode is selected by setting the manual mode bit in the control register. The block must be enabled for automatic execution (see the ***Control Block Execution*** section) for the block to function, even if there is no intention of using automatic control.

# Setpoint Tracking

Setpoint tracking provides a method for obtaining a smooth transition between manual and automatic process control. An operator may manually control an unstable process until it has stabilized; at which point, the operator will shift the block controller to automatic control. Setpoint tracking prevents a disturbance to the process at this point.

This result is accomplished by having the setpoint follow the process value as long as the block controller remains in manual. Were the setpoint not to do so, an error would exist at the time automatic control is engaged. This can lead to large fluctuations in the block controller output (OP) as the controller attempts to remove the error.

Changes to the setpoint, when the block is in manual mode, will be ignored.

# I/O Specification

The state of the I/O Specification bit determines how the values in the following block variables will be read:

- decrease output address (DO)
- inhibit execution input address (IH)
- increase output address (IO)
- block input source (IP)

Set this bit to 1 to use Modbus registers in these variables. Clear the bit to 0 to use absolute addresses in the these variables.

## Controllers with Firmware v. 1.23 or Newer

### *New Programs*

Set the I/O Specification bit to 1 in the control register, and use Modbus registers in the variables AO, DO, IH, IO and IP of all PID's. Select these registers from the user-written Register Assignment Table.

### *Old Programs*

When running a ladder logic or C Application program written for older firmware (v. 1.22 or older) there are two options:

1. Download the *Default Register Assignment Table* and make no changes to the program. (The I/O Specification bit will already be cleared to 0 in all PID control registers of the old program.)
2. Or, if a user-written Register Assignment Table is to be used, make the following changes to the program:
    - Set the I/O Specification bit to 1 in all PID block control registers.
    - Replace absolute addresses with Modbus registers in the variables AO, DO, IH, IO and IP of all PID's.

## Controllers with Firmware v. 1.22 or Older

The I/O Specification bit is not used by controllers with firmware versions 1.22 or older. Instead of a Register Assignment Table, these older versions have a fixed mapping of the I/O hardware to the I/O database. For these controllers, use absolute addresses in variables AO, DO, IH, IO and IP of all PID's and refer to the I/O Database section of *User Manual* supplied with the controller.

# Status Register

The block status register is a block variable which reports the status of certain conditions in a block. Application programs can read the status register at any time. The table below lists the individual bits of the status register and their significance.

| Bit | Value | Status |
|---|---|---|
| 0 | 1 | reserved for future use |
| 1 | 2 | BAD I/O ADDRESS error on input to block |
| 2 | 4 | high alarm condition on input to block |
| 3 | 8 | low alarm condition on input to block |
| 4 | 16 | external inhibit execution input is on |
| 5 | 32 | loop is outside of setpoint deadband |
| 6 | 64 | derivative gain clamped at maximum (rapid PV change) |
| 7 | 128 | BAD I/O ADDRESS error on output from block |
| 8 | 256 | block output clamped at full scale limit |
| 9 | 512 | block output clamped at zero scale limit |
| 10 | 1024 | reserved for future use |
| 11 | 2048 | control block is executing (not-necessarily in AUTO mode) |
| 12 | 4096 | alarm acknowledge bit |
| 13 | 8192 | control block is in manual mode |
| 14 | 16384 | reserved for future use |
| 15 | 32768 | reserved for future use |

An application program may test for a bit in the status register by ANDing the register with the value of the bit to be tested. If the result equals the value of the bit, the status condition signified by that bit exists.

## Alarm Acknowledge Bit

Bit 12 of the block status register SR is available to the application program for acknowledging that it is aware of an alarm. The alarm acknowledgment is the application program's way of indicating to the block controller that it is dealing with the situation. The bit will be cleared when the condition causing the alarm disappears, regardless of whether the program had acknowledged the alarm.

The application program will usually first be aware of the alarm when it sees that one of the alarm bits in SR has been set. Whenever one of these bits is set, the alarm output address specified by AO is turned on. This output will remain on even if the alarm condition disappears or is acknowledged. In this way, several block controllers can share the same alarm output address. The alarm output must be turned off by the application program when all alarms are either cleared or acknowledged.

The application program can use the acknowledge bit keep track of which block alarms have been acknowledged. When all blocks sharing an output have been handled, the output can be turned off.

### *Example:*

Three block controllers share the same alarm output address. If an alarm occurs on any of the blocks, a horn connected to the alarm output will sound. An application program is running which displays and logs alarms. The program will turn off the horn, when all alarms causing it have been acknowledged by an operator.

Each time the operator acknowledges a block alarm, the program sets the acknowledge bit for that controller. It then checks if the output may be turned off, by scanning all three controllers for unacknowledged alarm conditions. If it finds a block where there is an alarm, but the acknowledge bit is not set, then it does not turn off the horn.

# Control Block Execution

Some PID controllers, ratio/bias controllers and automatic alarm scanners require more frequent execution than others. The execution period may be set independently for each control block in the controller. The period may be as short as 0.1 seconds or as long as 6553.5 seconds.

A C application program sets the execution period with the **auto_pid** function. A ladder logic program sets the execution period with the **PID** function block. The execution period may be set by writing to the appropriate PID block execution period register in the I/O database.

Control blocks may be engaged bumplessly or non-bumplessly. These procedures are described below.

## Non-bumpless Engagement

Non-bumpless engagement puts a control block into operation without pre-calculating the integral required to keep the output at its current value. This method is used with P or PD controllers, ratio/bias controllers, and automatic alarm scanning. It can also be used with PID or PI controllers but the output of the controller may bump (make a sudden change) on the first execution of the controller.

Non-bumpless engagement is used when the control block execution period is set. A special procedure must be used if bumpless engagement is desired.

## Bumpless Engagement

Programs, which incorporate PID controllers, will often have functions that allow the operator to take a controller out of automatic execution. Additional operator commands can then be used to manually increase or decrease the output as desired. When the process has stabilized the operator can place the controller back into automatic. Given this scenario, it would be undesirable for the output of the controller to make a sudden jump. (It is assumed that the operator set the output to a particular value with good reasons.) Bumpless engagement engages controllers without upsetting the output

Bumpless engagement requires the pre-calculation a value of integral that prevents any change to the output of the controller on the first execution. Thereafter, the integral (and consequently the output) will change at a rate determined by the reset time as specified in the PID variable RE.

Bumpless engagement should never be used on a ratio/bias controller, an automatic alarm scanner, or a controller which does not have any reset action (P or PD). If bumpless engagement is used, on these types of controllers, the calculated value of integral which is stored in the controller will never change. Although this will cause no problems with ratio/bias controllers or automatic alarm scanning, the P and PD controllers will have a permanent output bias added.

The following algorithm pre-calculates the integral, assigns it to the control block and sets the block execution period. Note that the integral has the required two fixed decimal places because the gain has two fixed decimal places.

1. Calculate the required integral from the equation:

2. $$IN = \frac{(OP - OB)}{GA} - ER$$

3. Store the calculated integral to the IN register.
4. Set the block execution period.

The following sections show this algorithm implemented in the C and Ladder Logic languages.

## C Language Procedure

```
/* ---------------------------------------------------
   bumplessEngage

   Engage controlBlock bumplessly with the specified
   execution period.
   --------------------------------------------------- */

void bumplessEngage(unsigned controlBlock, unsigned period)
{
   int gain;
   int bias;
   int integral;
   int error;

   /* Read the current parameters from the block */

   gain   = get_pid( GA, controlBlock );
   error  = get_pid( ER, controlBlock );
   bias   = get_pid( OB, controlBlock );
   output = get_pid( OP, controlBlock );

   /* Calculate integral to maintain output */
   /* note: gain has two fixed decimal places */
   /* note: cast to long for precision of calculation */

   integral = ((long)output - bias) * 100 / gain - error;
   set_pid( IN, controlBlock, integral );

   /* Engage the control block */

   auto_pid( controlBlock, period );
}
```

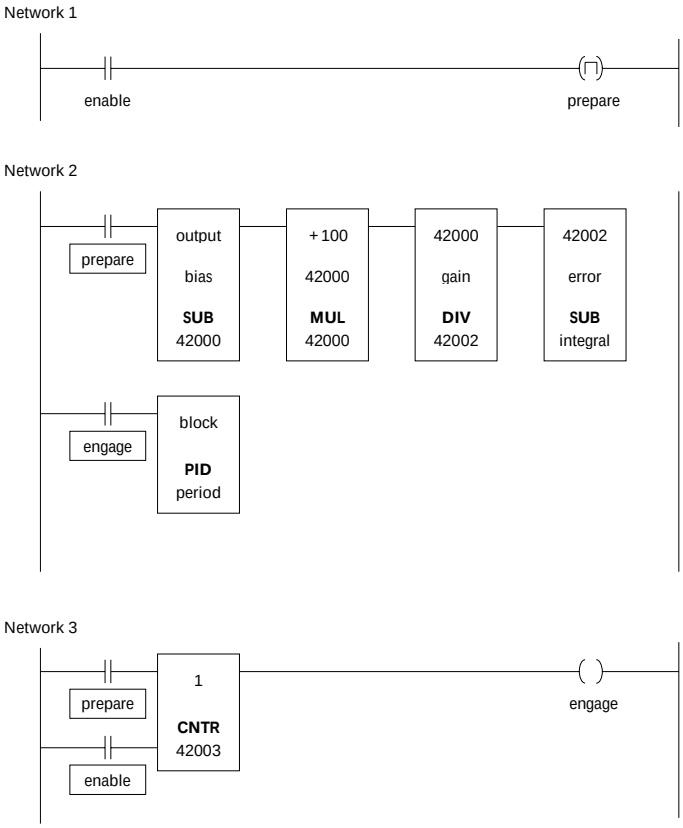
## Ladder Logic Procedure

The ladder logic networks shown below engage a PID block bumplessly. The PID block register numbers are not shown. Substitute the registers for the block you will use.

The calculation blocks use three registers (42000, 42001 and 42002) for storage of temporary results. The counter circuit ensures the calculation is performed before the PID block is engaged. The networks must be executed in the order shown for this circuit to work properly.

# Minimum Execution Periods

Controllers and alarm scanners will operate as frequently as ten times per second. It is possible to overload the background operations by requesting too many controllers to operate too frequently. When this happens, the controllers will execute less frequently than programmed. Application programs will also execute extremely slowly. To avoid this, the longest execution period acceptable to the process should be used for each controller.


Network 1
enable
prepare
Network 2
prepare
output
bias
SUB
42000
+100
42000
MUL
42000
42000
gain
DIV
42002
42002
error
SUB
integral
engage
block
PID
period
Network 3
prepare
enable
1
CNTR
42003
engage

# Configuring Control Blocks

The control block contains 24 block variables. Not all registers are used by all control algorithms. A systematic approach to configuration avoids confusion and improper configuration of control blocks. A recommended system is presented in this section.

## Register Assignment

For each required control block add a PID control block module to the Register Assignment Table and assign a range of Modbus registers to the control block. The contents of the control block registers are undefined. The first step is to clear all blocks that are required.

A C application program uses the **clear_pid** function to set all registers to 0.

A ladder logic program uses the **PUT** or **PUTU** function to write 0 into a block of registers. The function should be activated by a power up coil to prevent repeated clearing of the registers.

## Configuring PID Controllers

There are two types of PID controllers which may be defined. They are analog output controllers, and time proportioned output controllers. These controllers differ only in the configuration of the output and the selection of the execution period. Both types take their process value from an analog input.

Either type may also be connected for cascade control. Refer to the ***Configuring Cascade Controllers*** section.

### Analog Output

The following block variables must be specified for an analog output PID controller. Refer to the ***Block Output Types*** section for a full description of the variables.

| Variable | Description |
|---|---|
| CR | block control register |
| DB | Deadband |
| FS | full scale output (high limit) |
| GA | Gain |
| IB | block input bias |
| IO | increase output address |
| IP | block input source |
| OB | block output bias |
| RA | rate time (in 0.1 second increments) |
| RE | reset time (in 0.1 second increments) |
| SP | controller setpoint |
| ZE | zero scale output (low limit) |

Use the following steps to specify these block variables:

### *Step 1*

Calculate the setpoint and store it in the SP register.

**Example**: The setpoint for a temperature controller is 90 °C. The temperature signal comes from an instrument which is calibrated for 0 volts at 0 °C and 10 volts at 200 °C. The desired setpoint must be converted to a 16-bit signed number corresponding to the input from the I/O system. The following equation calculates the setpoint.

SP = (32767 x 90) / 200

### *Step 2*

Determine the source of the process value and store it in the IP register.

**Example**: The source of the process value of the above temperature controller is the analog input at Modbus register 30004. Therefore:

IP=30004.

### *Step 3*

Determine the input bias and store it in the IB register.

**Example**: The temperature controller is correctly calibrated so that an input bias is not necessary. The input bias term (if specified) is subtracted from the block input before the PID algorithm is executed. It is useful as an input zero term, but in this example, is not necessary. Therefore:

IB = 0.

### *Step 4*

Specify the proportional gain, reset time and rate time as follows. Note that the gain is stored as a two decimal place, fixed point number.

GA = gain x 100
RE = reset time in $10^{ths}$ of a second
RA = rate time in $10^{ths}$ of a second

**Example**: From a closed-loop response of the temperature controller, the gain is found to be 1.7, the reset time is found to be 4.6 seconds, and the rate gain is found to be 8 seconds. Therefore:

GA = 170
RE = 46
RA = 80

### *Step 5*

Specify the deadband if required. This block variable is optional. If no deadband is required, it should be set to zero. Then the controller will execute if any error exists.

**Example:** The deadband for the temperature controller is 2 °C. The instrument is calibrated for 0 to 10 volts over the 0 to 200 °C range. Each degree corresponds to an I/O count of 32767/200. Therefore

DB = 32767 / 200 x 2

### *Step 6*

Specify the output bias if required. This block variable is optional. If no output bias is required, it should be set to zero.

**Example**: The output for the temperature controller is a 0 mA to 20 mA analog output. With a 4-20 mA output, it is best to use a four mA output bias. Four mA corresponds to an I/O count of 6553. Using this bias sets the output to yield 4 mA when the controller output is 0. Therefore:

OB = 32767 * 4 / 20

### *Step 7*

Specify the full scale output in the FS register.

**Example**: The user wants to restrict the full scale output of the temperature controller to 18 mA. Therefore

FS = (32767 x 18) / 20

### *Step 8*

Specify the zero scale output in the ZE register.

**Example**: The zero scale output of the temperature controller should be clamped at 4 mA since the output is 4-20 mA. The output bias OB does not prevent the output from dropping below 4 mA. On negative errors the output would be below 4 mA even though an output bias is added. Therefore the zero scale limit should be programmed to prevent the controller from generating an illegal output less than 4 mA under all error conditions. Therefore

ZE = 32767 * 4 / 20

### *Step 9*

Specify the analog output register in the IO register.

**Example**: The temperature controller can supply heat to the system through the analog output at Modbus register 40021 which positions a steam control proportional valve. Therefore:

IO = 40021

### *Step 10*

Specify the block functions in the control register (CR).

**Example**: The temperature controller must be configured as follows:

| Function | Setting | Value |
|---|---|---|
| Block Output | analog channel | 2 |
| Block Input | analog channel | 8 |
| Setpoint Source | stored in SP | 0 |
| Block Function | PID | 32 |
| Alarms | none | 0 |
| Square Root of Error | no | 0 |
| Square Root of PV | no | 0 |
| I/O Specification | Modbus I/O | 16384 |
| Value of CR register | | 16426 |

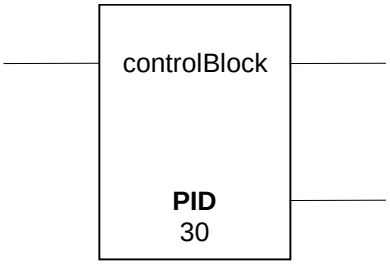
### *Step 11*

Determine the execution period. Start block auto-execution with the C **auto_pid** function or the ladder logic **PID** function block. If bumpless engagement is desired, the algorithm in the ***Bumpless Engagement*** section should be used.

**Example**: The temperature controller must execute every 3 seconds. A C application program will use the statement:

```
auto_pid( controlBlock, 30 );
```

A ladder logic program will use the function block:




## Time Proportioned Output

The following block variables must be specified for a time proportioned output, PID controller. Refer to the ***Configuring Control Blocks*** section for a full description of the variables.

| Variable | Description |
|---|---|
| CR | block control register |
| DB | Deadband |
| DO | decrease output address |
| FS | full scale output (high limit) |
| GA | Gain |
| IB | block input bias |
| IO | increase output address |
| IP | block input source |
| OB | block output bias |
| RA | rate time (in 0.1 second increments) |
| RE | reset time (in 0.1 second increments) |
| SP | controller setpoint |
| ZE | zero scale output (low limit) |

This controller is very similar to the analog output PID controller described in the previous sections. The differences are:

- The control register must be configured for a pulse duration or motor pulse duration output..
- Both the increase output and decrease output channels must be defined.
- The full and zero scale output limits must be modified.
- No output bias is normally used.
- The execution period must be adjusted to accommodate the characteristics of the control device and the process under control.

The first 5 steps of the configuration procedure are identical to the analog output controller, so no examples are provided.

## Step 1

Calculate the setpoint and store it in the SP register.

## Step 2

Determine the source of the process value and store it in the IP register.

## Step 3

Determine the input bias and store it in the IB register.

## Step 4

Specify the proportional gain, reset time and rate time as follows. Note that the gain is stored as a two decimal place, fixed point number.

GA = gain x 100
RE = reset time in $10^{ths}$ of a second
RA = rate time in $10^{ths}$ of a second

## Step 5

Specify the deadband if required. This block variable is optional. If no deadband is required, it should be set to zero. Then the controller will execute if any error exists.

## Step 6

Specify the output bias if required. The output bias is almost always 0.

## Step 7

Specify the full scale output in the FS register. This value is normally equal to the execution period of the block.

**Example**: The controller will execute once every 10 seconds. Therefore

FS = 100

## Step 8

Specify the zero scale output in the ZE register. For a dual acting controller this value is normally equal to –1 times the execution period of the block. For a single acting controller it is zero.

**Example**: The controller will execute once every 10 seconds. It is dual acting. Therefore:

ZE = –100

## Step 9

A dual acting controller has one digital output for a positive control action and another digital output for a negative control action. A single acting controller has a digital output for only the positive control action. The digital output addresses are specified in the block variables IO and DO.

**Example**: A positive control action of control block 7 is to be directed to coil 00022 and a negative control action directed to coil 00021. Therefore

IO = 00022
DO = 00021

## Step 10

Specify the block functions in the control register (CR).

**Example**: A pulse duration output will be used. The temperature controller must be configured as follows:

| Function | Setting | Value |
|---|---|---|
| Block Output | pulse duration | 1 |
| Block Input | analog channel | 8 |
| Setpoint Source | stored in SP | 0 |
| Block Function | PID | 32 |
| Alarms | none | 0 |
| Square Root of Error | no | 0 |
| Square Root of PV | no | 0 |
| I/O Specification | Modbus I/O | 16384 |
| Value of CR register | | 16384 |

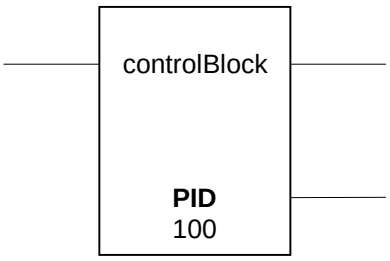
## Step 11

Determine the execution period. Start block auto-execution with the C **auto_pid** function or the ladder logic **PID** function block. If bumpless engagement is desired, the algorithm in the ***Bumpless Engagement*** section should be used.

**Example**: The temperature controller must execute every 10 seconds. A long scan period is used to improve the resolution of the output. A C application program will use the statement:

```
auto_pid( controlBlock, 100 );
```

A ladder logic program will use the function block:




# Configuring Ratio/Bias Controllers

The following block variables must be specified for an ratio/bias controller. Refer to the ***Control Block Variables*** section for a full description of the variables.

| Variable | Description |
|---|---|
| CR | block control register |
| FS | full scale output (high limit) |
| GA | Gain |
| IB | block input bias |
| IO | increase output address |
| IP | block input source |
| OB | block output bias |
| ZE | zero scale output (low limit) |

Use the following steps to specify these block variables:

## Step 1

Determine the source of the process value and store it in the IP register. The source is commonly the block output of another control block.

**Example**: The output of control block 6 controls the fuel flow to a combustion process. Control block 7 controls the air flow (open loop) to the same process, using a ratio controller. Therefore, the input of block 7 is

IP = 6

## Step 2

Specify the block ratio in the gain register. Note that the gain is stored as a two decimal place, fixed point number, so GA = ratio x 100.

**Example**: The output to the air damper must be 8.2 times the output to the fuel valve. Therefore

GA = 8.2 x 100 = 820

### Step 3

Specify the output and input biases if required. These block variables are optional. If no biases are required, they should be set to zero.

**Example**: An output bias of 230 is required for the air control. Also to zero the input signal a 12 bit number of 109 is required to be subtracted from the process value ( input bias ). Therefore

OB = 230
IB = 109

### Step 4

Specify the full and zero scale outputs according to the process restrictions.

**Example**: The air flow controller must never open more than 90 percent or less than 10 percent to ensure proper operation. Therefore

FS = 32767 x 0.90 = 29490
ZE = 32767 x 0.10 = 3276

### Step 5

A ratio/bias controller may have an analog output or a time proportioned output. Specify the analog output register in the IO register. Specify the time proportioned outputs in the IO and DO registers.

**Example**: The air valve position is determined by the analog output at holding register 40022. There is no decrease element since this is an analog output. DO need not be specified. Therefore

IO = 40022

### Step 6

Specify the block functions in the control register (CR).

**Example**: An analog output will be used. The air flow controller must be configured as follows:

| Function | Setting | Value |
|---|---|---|
| Block Output | Analog | 2 |
| Block Input | output of block IP | 4 |
| Setpoint Source | not used | 0 |
| Block Function | ratio/bias | 64 |
| Alarms | None | 0 |
| Square Root of Error | No | 0 |
| Square Root of PV | No | 0 |
| I/O Specification | Modbus I/O | 16384 |
| Value of CR register | | 16454 |

## Configuring Cascade Controllers

All P, PI, PD, PID and ratio/bias controllers may have their outputs cascaded to the setpoint of another controller. One of the controllers is called the Primary Controller. It's output is an internal output which is sent to the setpoint of the Secondary Controller. The output of the secondary controller can be analog, time proportioned (pulse duration or motor pulse duration) or internal (if additional cascading or simulation is being done).

PID and ratio/bias controller outputs may be cascaded indefinitely. In other words controller X may cascade into controller Y which may cascade into controller Z, and so on.

# Configuring the Primary Controller

This controller is configured the same as a single controller (refer to the previous sections) with one exception - the controller output is internal. Thus, in the previous sections, the following steps have to be changed:

## Control Register Step

The control register, must be programmed to define the output as internal. Therefore the only bits which change are as follows:

| Function | Setting | Value |
|---|---|---|
| Block Output | None | 0 |

## Output Channel Step

The output channel does not need to be defined.

# Configuring the Secondary Controller

This controller is configured the same as a single controller (refer to the previous sections) with one exception - the controller setpoint is cascaded from the primary controller's output. The only differences to the previous example are as follows:

## Setpoint Step

The setpoint need not be defined.

The source of the cascaded setpoint must be stored in register CA. It is the block number of the primary controller.

## Control Register Step

The control register, must be programmed to define the setpoint source as cascaded from the primary control block output. Therefore the only bits that change are as follows:

| Function | Setting | Value |
|---|---|---|
| Setpoint Source | from block CA | 16 |

**Example**: The output of controller 15 is to be cascaded to the setpoint of controller 20. The setpoint must be restricted to the range 6553 to 32767, as the process value is a 4-20 mA value.

First, define the two controllers as discussed previously. The primary controller should have an internal output.

Second, set the high and low output limits in the primary controller. This will ensure that the setpoint in the secondary controller does not fall outside of the 4-20 mA range. Thus,

$ZE_{15} = 6553$
$FS_{15} = 32767$

Third, define the setpoint source in the secondary controller (i.e. the source is the primary controller). Thus,

$CA_{20} = 15$

Fourth, enable cascade setpoint by turning on the cascade bit in the control register of the secondary controller. Thus,

$CR_{20}$ = function_values + 16

Finally, engage both controllers. For our example assume that both controllers will be activated with execution time of three seconds.

# Configuring Automatic Alarms

The following block variables must be specified for an automatic alarm. Refer to the ***Control Block Variables*** section for a full description of the variables.

| Variable | Description |
|---|---|
| AO | alarm output address |
| CR | block control register |
| HI | high alarm level |
| IP | block input source |
| LO | Low alarm level |

The above variables can be used in conjunction with any of the other control block functions, or can be used in a control block whose sole function is alarm testing.

Use the following procedure to configure automatic alarms:

## Step 1

Determine the source of the process value and store it in the IP register. As with the PID and ratio/bias controllers a source needs to be declared as an analog channel, a constant, or the output of another control block. This last option is useful in monitoring the output of a PID or ratio controller.

**Example**: Control block 7 will monitor analog input 30004. Therefore

$IP_7$ = 30004

## Step 2

Determine the block high and low alarm values in 12-bit quantities and assign to the high alarm (HI) and low alarm (LO) registers.

**Example**: An alarm is to occur if the block process value is higher than 82 percent of full scale or lower than 32 percent of full scale. Therefore:

$HI_7$ = 32767 x 0.82 = 26868
$LO_7$ = 32767 x 0.32 = 10485

## Step 3

Determine the alarm output address and store it in the AO register.

**Example**: The alarm is to be output at coil 00019. Therefore the alarm address is assigned as

$AO_7$ = 00019

## Step 4

Specify the block functions in the control register (CR).

**Example**: The control block has automatic alarms and an analog input source. The control block must be configured as follows:

| Function | Setting | Value |
|---|---|---|
| Block Output | None | 0 |
| Block Input | Analog | 8 |
| Setpoint Source | not used | 0 |
| Block Function | alarms only | 0 |
| Alarms | Enabled | 128 |
| Square Root of Error | No | 0 |
| Square Root of PV | No | 0 |
| I/O Specification | Modbus I/O | 16384 |
| Value of CR register | | 16384 |

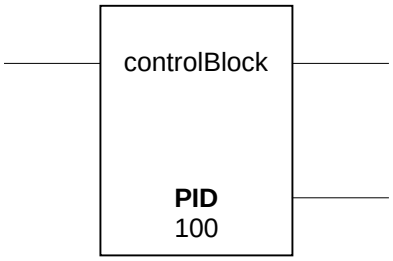
### Step 5

Determine the execution period. Start block auto-execution with the C **auto_pid** function or the ladder logic **PID** function block.

**Example**: The automatic alarms are to be tested every 10 seconds. A C application program will use the statement:

```
auto_pid( controlBlock, 100 );
```

A ladder logic program will use the function block:




## Disabling Automatic Alarms

Sometimes automatic alarms in a PID or ratio/bias control block need to be disabled. To disable the alarms, clear the alarm enable bit (bit 7) in the control register. In a C application program use this routine:

```
void disableAlarms( unsigned controlBlock )
{
   unsigned controlRegister;

   controlRegister = get_pid( CR, controlBlock );
   controlRegister &= 0xFF7F;
   set_pid( CR, controlBlock, controlRegister );
}
```

In a ladder logic program, it is easiest to assign a new value to the control register that does not enabled the automatic alarms.

Setting the execution period to zero also prevents automatic alarm scanning, but has the added effect of shutting off any PID or ratio/bias controller in the same block. For alarm only blocks, setting the execution period to zero is the easiest way to disable alarms.

# Configuration Examples

This section illustrates practical configurations of the TelePACE PID control blocks. Specific examples are given for the most common configurations. More complicated applications are combinations of these common, simple configurations.

Where applicable, a diagram is provided with the example to illustrate the configuration of a control block for the function described. The diagrams are similar to ***Figure 8*****.** It shows the most general configuration of a control block, with all possible process inputs and outputs.

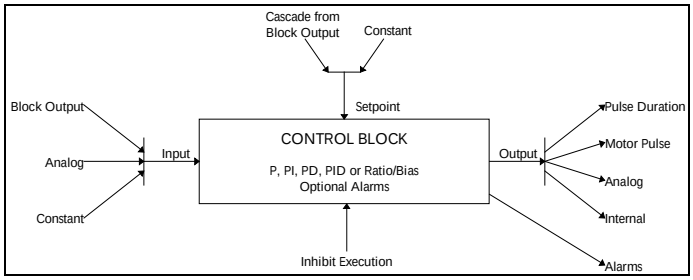



***Figure 8: Control Block with All Inputs and Outputs***

The solutions given in the examples describe the configuration in a general format. Refer to the ***Accessing Control Blocks*** section for details on implementing the solutions in the C and Ladder Logic languages.

## Alarms: High Alarm

### High Temperature In A Dryer

Waste sawdust is used as a fuel for a boiler to provide the steam requirements of a sawmill. The moisture content of the sawdust must be lowered from 23% to 18% for efficient combustion. The sawdust is dried in a rotary dryer before passing onto the burners.

It is desired that the temperature in the rotary dryer not exceed 290 °C to prevent the burning of the sawdust and damage to the dryer. A thermocouple has been installed to measure the dryer off-gas temperature and is read on analog input 30004. A temperature of 290 °C corresponds to an unscaled 16 bit precision number of 24720. The alarm must be checked every 2 seconds.

How would a block controller on the controller be configured to ring an alarm that has been connected to digital output at coil 00029 when the temperature exceeds 290 °C?

#### Solution

The following information was extracted from the example:

- The 16 bit high alarm level is 24720.
- The input is read from analog input 30004.
- The alarm will be rung on coil 00029.

The control register must be configured as follows:

| Function | Setting | Value |
|---|---|---|
| Block Output | none | 0 |
| Block Input | analog input | 8 |
| Setpoint Source | not used | 0 |
| Block Function | alarms only | 0 |
| Alarms | enabled | 128 |
| Square Root of Error | no | 0 |
| Square Root of PV | no | 0 |
| I/O Specification | Modbus I/O | 16384 |
| Value of CR register | | 16520 |

The following entries will configure a control block to detect and trigger the high alarm. See ***Figure 9*** for a block diagram of the controller.

| Variable | Value | Comment |
|---|---|---|
| IP | 30004 | Input from analog input 30004 |
| HI | 24720 | 290 °C corresponds to 24720 |
| AO | 00029 | Alarm bell is attached to coil 00029 |
| CR | 16520 | See table above |
| Period | 20 | Execute every 2 seconds |

# Alarms: High and Low Alarms

## Low and High Temperature in a Dryer

In the system of the previous example, the dried sawdust must not be below 200 °C before entering the burners for the steam boiler. A temperature of 200 °C corresponds to an unscaled 16 bit precision number of 16080. The same alarm bell can be used for either high or low alarms. How would the block controller be configured to ring the alarm when the temperature is under 200 °C?

### Solution

The following additional information was extracted from the example:

- The 16 bit low alarm level is 16080.
- The same high alarm level and control register configuration is used.

The configuration is identical to the previous example except for the addition of the low alarm setpoint. The following entries will configure a control block to detect and trigger the high alarm. See ***Figure 9*** for a block diagram of the controller.

| Variable | Value | Comment |
|---|---|---|
| IP | 30004 | Input from analog input 30004 |
| HI | 24720 | 290 °C corresponds to 24720 |
| LO | 16080 | 200 °C corresponds to 16080 |
| AO | 00029 | Alarm bell is attached to coil 00029 |
| CR | 16520 | See table above |
| Period | 20 | Execute every 2 seconds |

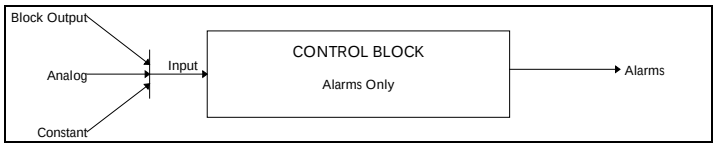



***Figure 9: Alarm Testing Block Inputs and Outputs***

# PID Control: Analog Output

## Temperature Control on a Heated Tank

Sulfuric acid is electrically heated in a continuous flow stirred tank before being used to leach a copper, nickel and iron bearing ore concentrate. The heater is supplied current as determined from the output of holding register 40018. The acid flow fluctuates since it is taken from the recycle of a semi-batch process.

Due to these fluctuations, a PID controller is required to maintain the temperature at a setpoint of 90 °C (corresponding to an unsigned number 28536, read on analog input 30004). It is only necessary to execute control once every 10 seconds. An open-loop response experiment yielded these tuning parameters:

- GAIN = 11.2 (dimensionless gain)
- RESET TIME = 47 seconds
- DERIVATIVE TIME = 109 seconds

How would a block controller be configured to perform this function?

### Solution

The following information was extracted from the example:

- The 16 bit setpoint is 28536.
- The gain is 11.2.
- The reset time is 470 tenths of a second.
- The derivative time is 1090 tenths of a second.
- The input is analog input register 30004.
- The output is holding register 40018.

The control register must be configured as follows:

| Function | Setting | Value |
|---|---|---|
| Block Output | analog channel | 2 |
| Block Input | analog channel | 8 |
| Setpoint Source | stored in SP | 0 |
| Block Function | PID | 32 |
| Alarms | none | 0 |
| Square Root of Error | no | 0 |
| Square Root of PV | no | 0 |
| I/O Specification | Modbus I/O | 16384 |
| Value of CR register | | 16426 |

The following entries will configure a control block to perform the required control. See ***Figure 10*** for a block diagram of the PID controller.

| Variable | Value | Comment |
|---|---|---|
| SP | 28536 | corresponds to the 90 °C setpoint |
| IP | 30004 | read temperature from 30004 |
| GA | 1120 | open loop response value x 100 |
| RE | 470 | open loop response value x 10 |
| RA | 1090 | open loop response value x 10 |
| IO | 40018 | output to heater on 40018 |
| CR | 16426 | see table above |
| FS | 32767 | allow full range of output values (0..32767) |
| ZE | 0 | allow full range of output values (0..32767) |
| Period | 100 | execute every 10 seconds |

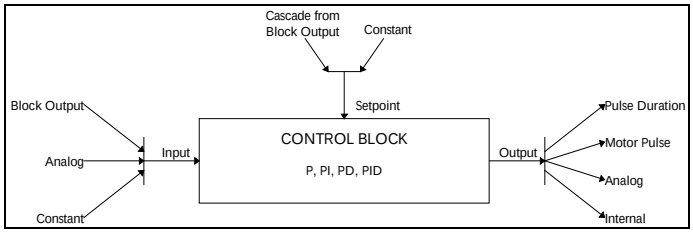



***Figure 10: General Block Diagram for PID Control***

# PID Control: Analog Output and Alarms

## Temperature Control on a Heated Tank

The sulfuric acid used in the process described in the previous example boils at a temperature of 103 °C. Also, the leaching rate for iron is negligible if the acid is below 75 °C.

How would the block controller be configured to detect temperatures below 75 °C (read as 27416 on analog input 30004) and above 103 °C (read as 29608 on 30004), ring an alarm bell connected to coil 00025, as well as perform PID control?

### Solution

The following additional information was extracted from the example.

- The setpoint and tuning parameters are the same as for the previous example.
- The 16 bit high alarm level is 29608.
- The 16 bit low alarm level is 27416.
- The alarm output is directed to coil register 00025.

The control register must be configured as follows:

| Function | Setting | Value |
|---|---|---|
| Block Output | analog channel | 2 |
| Block Input | analog channel | 8 |
| Setpoint Source | stored in SP | 0 |
| Block Function | PID | 32 |

| Function | Setting | Value |
|---|---|---|
| Alarms | enabled | 128 |
| Square Root of Error | no | 0 |
| Square Root of PV | no | 0 |
| I/O Specification | Modbus I/O | 16384 |
| Value of CR register | | 16554 |

The following entries will configure a control block to perform the required control. See ***Figure 10*** for a block diagram of the PID controller.

| Variable | Value | Comment |
|---|---|---|
| SP | 28536 | corresponds to the 90 °C setpoint |
| IP | 30004 | read temperature from register 30004 |
| GA | 1120 | open loop response value x 100 |
| RE | 470 | open loop response value x 10 |
| RA | 1090 | open loop response value x 10 |
| IO | 40018 | output to heater on 40018 |
| CR | 16554 | see table above |
| FS | 32767 | allow full range of output values (0..32767) |
| ZE | 0 | allow full range of output values (0..32767) |
| HI | 29608 | corresponds to 103 °C high alarm |
| LO | 27416 | corresponds to 75 °C low alarm |
| AO | 00025 | coil 00025 |
| Period | 100 | execute every 10 seconds |

# PID Control: Single Acting Time Proportioned Output

## pH Control On a Continuous Stirred Tank Reactor

A reaction is taking place in a Continuous Stirred Tank Reactor (CSTR) that consumes acid. It was determined that the optimum pH for the reaction is 3.2. The output from a pH meter is read on analog input 30008 and a pH reading of 3.2 corresponds to the 16-bit precision number 10328.

The acid is fed to the process by a fixed speed pump, that can be turned on or off by a digital output at coil 00026. An open-loop response experiment yielded these tuning parameters:

- GAIN = –1.2 (dimensionless gain)
- RESET TIME = 122 seconds
- DERIVATIVE TIME = 39 seconds

How would a block controller be configured to perform PID control with pulse duration output?

### Solution

This is an example of single acting control. If the pH is above the setpoint then acid is added. Also, note that the dimensionless gain is negative. This indicates that a positive control action is required when a negative error occurs. A negative gain is used when negative control action is required for a positive error. (The negative gain is also predicted by the open-loop tuning technique.)

The following information was extracted from the example:

- The 16 bit setpoint is 10328.
- The gain is –1.2.
- The reset time is 1220 tenths of a second.
- The derivative time is 390 tenths of a second.
- The input is taken from analog input 30004.
- Output is directed to coil 00026.
- The full scale output 200 tenths of a second (equal to sampling period).
- The zero scale output is 0.

The control register must be configured as follows:

| Function | Setting | Value |
|---|---|---|
| Block Output | pulse duration | 1 |
| Block Input | analog channel | 8 |
| Setpoint Source | stored in SP | 0 |
| Block Function | PID | 32 |
| Alarms | None | 0 |
| Square Root of Error | No | 0 |
| Square Root of PV | No | 0 |
| I/O Specification | Modbus I/O | 16384 |
| Value of CR register | | 16425 |

The following entries will configure a control block to perform the required control. See ***Figure 10*** for a block diagram of the PID controller.

| Variable | Value | Comment |
|---|---|---|
| SP | 10328 | corresponds to pH of 3.2 |
| IP | 30004 | read pH from analog input 30004 |
| GA | –120 | open loop response value x 100 |
| RE | 1220 | open loop response value x 10 |
| RA | 390 | open loop response value x 10 |
| ZE | 0 | no negative output for single acting control |
| FS | 200 | maximum on time is equal to execution period |
| IO | 00026 | coil 00026 |
| CR | 16425 | see table above |
| period | 200 | execute every 20 seconds |

# PID Control: Dual Acting Time Proportioned Output

## pH Control on a Continuous Stirred Tank Reactor

In the system of the previous example, it was decided to add caustic soda (a strong base) if the pH was below setpoint. Since a strong acid was used, a pump to deliver the caustic was chosen that had the same pumping capacity as the acid pump.

The caustic pump can be turned on with digital output at coil 00027. How could the block controller be re-configured for this dual-acting control?

### Solution

The following information was extracted from the example:

- The setpoint, tuning parameters and control register configuration are the same as in the previous example.
- Since the pulse duration output has a negative as well as a positive control action, the zero scale output must be set equal to the negative value of the execution period in tenths of a second (i.e. –200 tenths).
- The decrease digital output is coil 00027.
- A deadband must be used to prevent the conflicting action of the outputs as the process error approaches zero. This is arbitrarily assigned a value of 10.

The following entries will configure a control block to perform the required control.

| Variable | Value | Comment |
|---|---|---|
| SP | 10328 | corresponds to pH of 3.2 |
| IP | 30004 | read pH from analog input 30004 |
| GA | –120 | open loop response value x 100 |
| RE | 1220 | open loop response value x 10 |
| RA | 390 | open loop response value x 10 |
| ZE | –200 | maximum decrease output on-time equal to execution period |
| FS | 200 | maximum increase output on-time equal to execution period |
| IO | 00026 | coil 00026 |
| DO | 00027 | coil 00027 |
| CR | 16425 | see table in previous example |
| DB | 10 | deadband prevents addition of both acid and base |
| period | 200 | execute every 20 seconds |

# PID Control: Cascade Controllers

## Furnace Temperature Control

A furnace (soaking pit) is used to heat cold steel slabs to 1050 °C before being hot rolled to strip steel. Off gases (methane and other hydrocarbons) from coke ovens are used to heat the furnace. A flow meter monitors the gas flow rate and the output of this meter is monitored on analog input 30002.

The flow can be continuously adjusted with a valve whose position is determined by the output of holding register 40021. A closed-loop tuning experiment (using the Ziegler-Nichol method) produced the following tuning constants for a PID flow controller:

- GAIN = 201 (dimensionless gain)
- RESET = 2.1 (seconds)
- DERIVATIVE = 4.6 (seconds)

The temperature of the furnace is to be controlled by manipulating the setpoint of the fuel-gas flow controller (cascade control). A thermocouple has been installed inside the furnace and the temperature is monitored on analog input 30001.

A temperature of 1050 °C corresponds to an unscaled number of 18440. An open-loop experiment produced the following constants for the PID temperature controller:

- GAIN = 19.2 (dimensionless gain)
- RESET = 490 (seconds)
- DERIVATIVE = 620 (seconds)

How would a block controller be configured to implement cascade control of the furnace temperature?

## Solution

Two control blocks are required to implement the temperature control: one to control the flow rate of the fuel-gas, the other to control the temperature by manipulating the setpoint of the flow controller. The following information was extracted from the example for the fuel-gas flow controller:

- The gain is 201.
- The reset time is 21 tenths of a second.
- The derivative time is 46 tenths of a second.
- The input is taken from analog channel 30002.
- Output is directed to analog output 40021.
- The setpoint is taken from the output of the temperature controller.

The control register must be configured as follows:

| Function | Setting | Value |
|---|---|---|
| Block Output | Analog channel | 2 |
| Block Input | Analog channel | 8 |
| Setpoint Source | From block CA | 16 |
| Block Function | PID | 32 |
| Alarms | None | 0 |
| Square Root of Error | No | 0 |
| Square Root of PV | No | 0 |
| I/O Specification | Modbus I/O | 16384 |
| Value of CR register | | 16442 |

The following entries will configure the fuel gas flow controller using block 0. See ***Figure 11*** for a block diagram of the cascaded PID controllers.

| Variable | Value | Comment |
|---|---|---|
| $CA_0$ | 7 | Setpoint comes from block 7 |
| $IP_0$ | 30002 | read gas flow from 30002 |
| $GA_0$ | 20100 | Closed loop response value x 100 |
| $RE_0$ | 21 | Closed loop response value x 10 |
| $RA_0$ | 46 | Closed loop response value x 10 |
| $IO_0$ | 40021 | Output to flow value actuator analog output 40021 |
| $CR_0$ | 16442 | see table above |
| $FS_0$ | 32767 | allow maximum range of output (0..32767) |

| | | |
|---|---|---|
| $ZE_0$ | 0 | allow maximum range of output (0..32767) |
| period | 200 | Execute every 20 seconds |

The following information was extracted from the example for the temperature controller:

- The 16 bit setpoint is 18440.
- The gain is 19.2.
- The reset time is 4900 tenths of a second.
- The derivative time is 6200 tenths of a second.

The control register must be configured as follows:

| Function | Setting | Value |
|---|---|---|
| Block Output | None | 0 |
| Block Input | Analog channel | 8 |
| Setpoint Source | Stored in SP | 0 |
| Block Function | PID | 32 |
| Alarms | None | 0 |
| Square Root of Error | No | 0 |
| Square Root of PV | No | 0 |
| I/O Specification | Modbus I/O | 16384 |
| Value of CR register | | 16424 |

The following entries will configure the temperature controller using block 7.

| Variable | Value | Comment |
|---|---|---|
| $SP_7$ | 18440 | Corresponds to 1050 °C setpoint |
| $IP_7$ | 30001 | read temperature from 30001 |
| $GA_7$ | 1920 | Closed loop response value x 100 |
| $RE_7$ | 4900 | closed loop response value x 10 |
| $RA_7$ | 6200 | closed loop response value x 10 |
| $CR_7$ | 16424 | see table above |
| $FS_7$ | 32767 | upper limit of setpoint for block 0 |
| $ZE_7$ | 0 | lower limit of setpoint for block 0 |
| period | 200 | execute every 20 seconds |

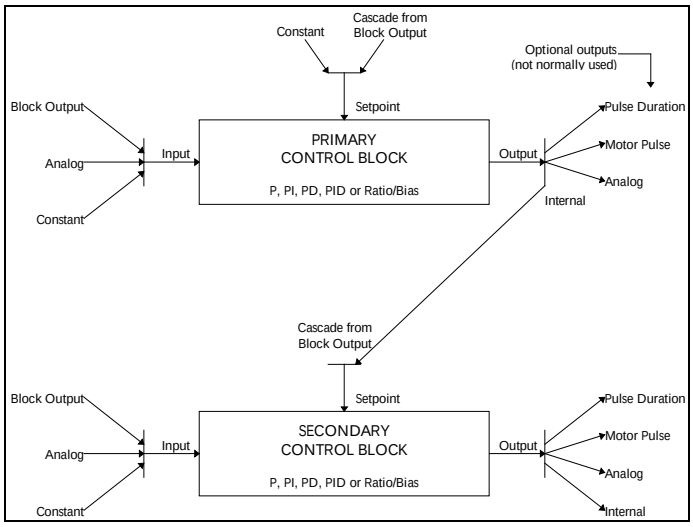



***Figure 11: Cascade Control Block Diagram***

# PID Control: Square Root Linearization for Flow Control

## Liquid Flow Control

Water is flowing through a pipe from a constant pressure source to a dilution tank. The flow is manipulated by a linear control valve whose position can be adjusted by analog output 40018. A U-tube manometer filled with mercury measures the pressure (and hence, the flow-rate) of the water as indicated by the height of the mercury.

The height of the mercury is continuously monitored by analog input 30002. A flow of 14 USGPM is desired and is read on analog input 30002 as a unscaled number of 1089. A minimum flow that corresponds to a 16 bit number 776 on the analog output is also required. A closed-loop response experiment provided the following PID tuning constants:

- GAIN = .7 (dimensionless gain)
- RESET = 1.2 (seconds)
- RATE = 2.4 (seconds)

How would a block controller be configured to perform the flow control?

### Solution

From the Bernouille equation, the flow of water through a pipe is proportional to the square root of the pressure difference or the head height (measured by the manometer). To obtain the flow reading from the manometer height read from analog input 30002, the square root must be taken of the process value.

The following information was extracted from the example:

- The 16 bit setpoint is 33 * 128 (the normalized square root of 1089)
- The gain is 0.7.
- The reset time is 12 tenths of a second.
- The derivative time is 24 tenths of a second.
- The input is read from analog input 30002.

- The controller output is directed to 40018.
- The 16 bit full scale output is 32767.
- The 16 bit zero scale output is 776.

The control register must be configured as follows:

| Function | Setting | Value |
|---|---|---|
| Block Output | analog channel | 2 |
| Block Input | analog channel | 8 |
| Setpoint Source | stored in SP | 0 |
| Block Function | PID | 32 |
| Alarms | none | 0 |
| Square Root of Error | no | 0 |
| Square Root of PV | yes | 512 |
| I/O Specification | Modbus I/O | 16384 |
| Value of CR register | | 16938 |

The following entries will configure a control block to perform the required control.

| Variable | Value | Comment |
|---|---|---|
| SP | 4224 | corresponds to normalized square root of 1089 |
| IP | 30002 | read manometer input from analog input 30002 |
| GA | 70 | closed loop response value x 100 |
| RE | 12 | closed loop response value x 10 |
| RA | 24 | closed loop response value x 10 |
| IO | 40018 | output to valve actuator on analog output 40018 |
| CR | 16938 | see table above |
| FS | 32767 | allow output to reach maximum value |
| ZE | 776 | limit minimum value of output |
| period | 10 | execute every second |

# Output Tracking

## Combustion Air Control

The flow of combustion air to the furnace of the cascade control example is also controlled. The required air flow is 3 times the flow of the fuel-gas. A linear valve controls the flow of the air. The valve position is determined by the output of analog output 40021.

How would a block controller be configured to control the air flow?

### Solution

The following information was extracted from the example.

- The control block in the cascade control example does not need to be reconfigured.
- The gain of the air flow controller is 3.
- The output of the controller is directed to analog output 40021.

- The controller input comes from the fuel-gas control block output (block 7).

The control register must be configured as follows:

| Function | Setting | Value |
|---|---|---|
| Block Output | analog channel | 2 |
| Block Input | from block IP | 4 |
| Setpoint Source | not used | 0 |
| Block Function | ratio/bias | 64 |
| Alarms | none | 0 |
| Square Root of Error | no | 0 |
| Square Root of PV | no | 0 |
| I/O Specification | Modbus I/O | 16384 |
| Value of CR register | | 16454 |

The following entries will configure a control block 8 to perform the required control.

| Variable | Value | Comment |
|---|---|---|
| $GA_8$ | 300 | ratio x 100 |
| $IP_8$ | 7 | block input comes from block 7 |
| CR | 16454 | see table above |
| IO | 40021 | output to control valve actuator on analog output 40021 |
| FS | 3120 | limit maximum output to valve actuator |
| ZE | 1200 | limit minimum output to valve actuator |
| period | 20 | execute every 2 seconds |

# Ratio Control

## Reagent Additions to a Continuous Stirred Tank Reactor

Waste water is flowing into a Continuous Stirred Tank Reactor (CSTR) where alum is added. The amount of alum added is proportional to the flow of water through the reactor. A flow meter is read on analog input 30005. Output to the alum metering is via analog output 40022. A ratio of 7.2 is required.

How would a block controller be configured to control the alum addition?

### Solution

The following information was extracted from the example:

- The input is taken from analog input 30005.
- The output is directed to analog output 40022.
- The ratio gain is 7.2.
- No output bias is required.

The control register must be configured as follows:

| Function | Setting | Value |
|---|---|---|
| Block Output | analog channel | 2 |
| Block Input | analog channel | 8 |
| Setpoint Source | not used | 0 |

| Function | Setting | Value |
|---|---|---|
| Block Function | ratio/bias | 64 |
| Alarms | none | 0 |
| Square Root of Error | no | 0 |
| Square Root of PV | no | 0 |
| I/O Specification | Modbus I/O | 16384 |
| Value of CR register | | 16458 |

The following entries will configure a control block to perform the ratio/bias control.

| Variable | Value | Comment |
|---|---|---|
| GA | 720 | ratio x 100 |
| IP | 30005 | read flow on analog input 30005 |
| CR | 16458 | see table above |
| IO | 40022 | output to metering pump on analog output 40022 |
| FS | 32767 | allow maximum range of output |
| ZE | 0 | allow maximum range of output |
| period | 10 | execute every second |

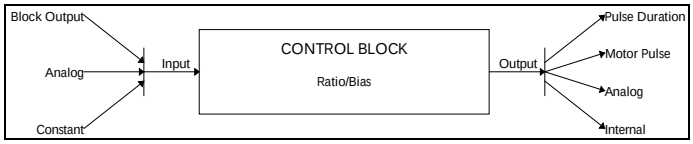



***Figure 12: Ratio/Bias Control Block Diagram***

# Batch Control

The following example illustrates how seven control blocks can be used to control a batch process.

***Figure 13*** shows the batch system. Three liquid reagents (A, B and C) are added in a fixed ratio to the main stream. The flow rate of the main stream is measured and controlled by a PID controller.

The output of this controller is fed to three ratio controllers. The output of each ratio controller is the setpoint of a PID control block for each of the reagents. The flow rate is controlled by the PID algorithm.

A high alarm for an output of zero automatically turns off the pump if the output of the controller is zero, preventing overheating (this irregular use of an alarm output illustrates that control blocks are limited only by the imagination).

Such a configuration facilitates the changing of the batch recipe. If the recipe changes for the batch process, then each ratio controller gain can be adjusted in proportion.

Adjustments to increase the flow through-put of the batch are accomplished by the single adjustment of the setpoint of the main flow control block. The additional demand for the reagents is automatically handled by the ratio controllers.

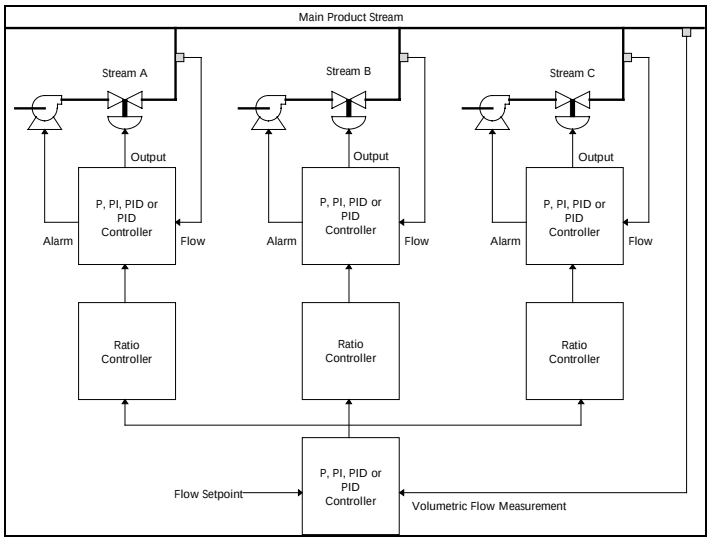



***Figure 13: Batch Process Schematic***

# Tuning PID Control Blocks

PID controllers must be tuned before they can be used. This process consists of determining the parameters K, T and R, known collectively as tuning parameters. These parameters vary from depending upon the process, the sensors used, and the control element. In this section methods will be outlined to obtain these parameters.

Tuning techniques may be categorized into two classes: open loop tuning and closed loop tuning. In open loop tuning, the response of the process value to a step change in the control element's output is used to obtain the proportional gain, the reset time and the rate gain. The PID controller is not coupled to the process.

In closed loop tuning, the response of the process coupled to the PID controller is used to determine the parameters. Each method has its advantages. The Ziegler-Nichol technique will be discussed as a closed loop method and the Cohen-Coon technique will be discussed as an open loop technique.

It is recommended that this section be read and understood thoroughly, even if the reader is familiar with these techniques, as the SCADAPack and TeleSAFE controllers use dimensionless proportional gain to speed the execution of the algorithm.

## Closed Loop Tuning: The Ziegler-Nichol Method

The Ziegler-Nichol tuning method is used for processes with quick response and little dynamic lag (i.e. the process value responds quickly to a change in the control element). Processes with lag times of less than 30 seconds can be tuned using this method. The parameters derived are be to used only as initial estimates. Further fine tuning is required to achieve the optimum control settings.

The technique is:

1. Close the control loop with the a PID control block:
    - Select a control block.
    - Specify the analog channel from which the process value will be read.
    - Specify ZE as 0 and FS as 32767.
    - Specify the output channel. The control element should be on this channel.
    - Arbitrarily assign a setpoint. This setpoint is dimensionless and must be within the range of 0 to 32767. The setpoint must not exceed the safe operational limits of the process.
    - Set the control register to an appropriate configuration.
    - Set the sampling period to 1 second.
2. The process response must be recorded. A data acquisition program must be written to record the time and the process value. Run the data acquisition program.
3. Slowly increase the gain of the PID controller until a steady state oscillation is detected in the process value. It may be necessary to make a change in the setpoint to start the oscillation (a change of +/– 1000 is adequate).
4. Record the gain $K_u$ when a steady state oscillation has been achieved. The experiment is over and the controller may be turned off.

5. Plot the process response for the gain that caused the steady state error. (The response was recorded by the data acquisition program.)
6. Determine the period of oscillation $P_u$ from the response as shown in ***Figure 14***.
7. Determine the P, PI or PID parameters from the values of $K_u$ and $P_u$ using the table below.

| **Controller** | ***K*** | ***T*** | ***R*** |
|---|---|---|---|
| Proportional | 0.5 x $K_u$ | | |
| Proportional-Integral | 0.45 x $K_u$ | $P_u$/1.2 | |
| Proportional-Integral-Derivative | 0.6 x $K_u$ | $P_u$/2 | $P_u$/8 |

Once the required parameters have been found, configure the controller as described in previous sections of the manual, and start the controller executing. The controller is now operating in real time and can be tested for response and fine tuned as required.

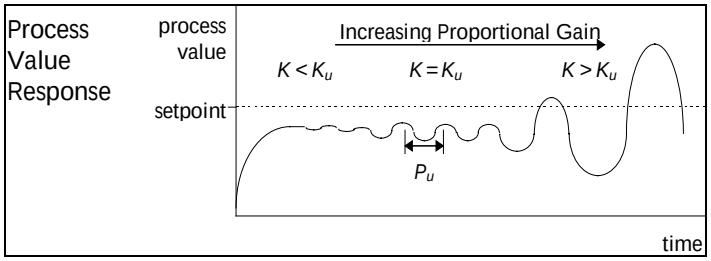



***Figure 14: Ziegler-Nichol Response Characteristics***

# Open Loop Tuning: The Cohen-Coon Method

The Cohen-Coon technique is simplistic when compared to the closed loop method. It is best used when a response time of greater than 30 seconds exists in the process. It should not be used for response times less than 30 seconds. As with the Ziegler-Nichol method, this method yields only rough estimates of the PID parameters and fine tuning may be necessary.

The technique is:

1. Run the data acquisition program.
2. Set the output of the control element at an arbitrary dimensionless number in the range of 0 to 32767. Record this number.
3. Wait for the process to reach steady state.
4. Introduce a step increase in the output to the control element. Record this new output and the time of the step increase.
5. Wait for the process to reach steady state.
6. Plot the response. Plot the process value on the Y-axis and the elapsed time (in seconds) from the step increase, on the X-axis.
7. Obtain $T_d$ and $T_r$ from the response curve as shown in ***Figure 15*** below.
8. Calculate $K_p = B_u/M$ where $M$ is the magnitude of the step change.
9. Calculate the PID tuning parameters from $K_p$, $T_d$ and $T_r$ using the table below.

| Controller | *K* | *T* | *R* |
|---|---|---|---|
| Proportional | $\frac{T_r}{K_p \times T_d}\left(1+\frac{T_d}{3T_r}\right)$ | | |
| Proportional-Integral | $\frac{T_r}{K_p \times T_d}\left(0.9+\frac{T_d}{12T_r}\right)$ | $\frac{T_d \times \left(30+\frac{3T_d}{T_r}\right)}{9+\frac{20T_d}{T_r}}$ | |
| Proportional-Integral-Derivative | $\frac{T_r}{K_p \times T_d}\left(\frac{4}{3}+\frac{T_d}{4T_r}\right)$ | $\frac{T_d \times \left(32+\frac{6T_d}{T_r}\right)}{13+\frac{8T_d}{T_r}}$ | $\frac{4T_r}{11+\frac{2T_d}{T_r}}$ |

Once the required parameters have been found, configure the controller as described in previous sections of the manual, and start the controller executing. The controller is now operating in real time and can be tested for response and fine tuned as required.

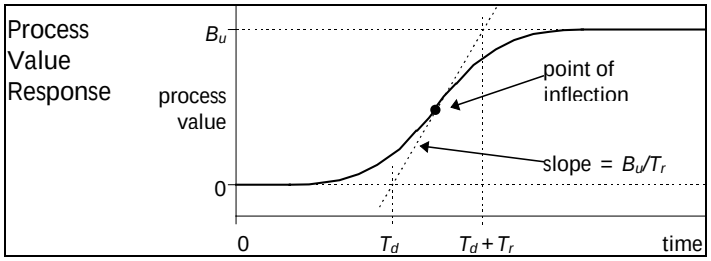



***Figure 15: Cohen-Coon Response Characteristics***

# Fine Tuning

After testing the response of the PID controller, it may be necessary to fine tune. The table below lists symptoms of a poor response and recommended remedies.

| Problem | Recommended Remedy |
|---|---|
| Overshoot of setpoint is too large | Decrease gain |
| Response is too slow | Increase gain and/or decrease reset time. Increasing rate gain may help. |
| Response is oscillatory | Decrease gain and/or increase reset time. Decreasing the scan time may help. |
| Steady state offset | Decrease reset time. |
| Response starts fast but slow to reach setpoint | Decrease reset time. |

# Selecting the Execution Period

The execution period is the interval at which a control block executes. The selection of a proper execution period is important. Improper selection can result in unstable control. The method of selection is different depending upon whether an analog output or time

proportioned output is used by the control block. The sections below describe qualitative criteria for choosing the period.

The Jury Stability Test is a quantitative method of determining an adequate execution period, but the details of this mathematical approach are left to the references. In most cases, the selection of a period can be judgmental, as long as the principles described below are followed.

## PID or Ratio/Bias Controllers

Execution periods should be as short as possible while avoiding unnecessary slowing of any application programs that may be running in the foreground. Long periods should be avoided since these can cause unstable control. As a rule of thumb for PID control, the period should be less than the reset time.

## Time Proportioned Output Controllers

Execution periods should be as long as possible to improve the resolution of the pulse output. Also, if pumps are being controlled by the digital output, the infrequent starts will decrease wear. Once again, excessively long periods could result in unstable control.

# Advanced Control

Control schemes on the controller are not limited to those provided in the control blocks. The C and Ladder Logic languages contain all of the I/O statements required to program sophisticated control algorithms for regulating processes that are uncontrollable using PID or ratio/bias controllers. The I/O statements are easily learned. Refer to the C Tools or Ladder Logic user manual for explanations of the I/O commands.

This section outlines how advanced algorithms may be programmed. A working knowledge of the application language is assumed, as well as a thorough knowledge of modern control theory. Readers unfamiliar with modern digital control theory are recommended to read "Digital Control Systems" by Kuo. This book is an excellent source of information upon how to approach control problems using the digital computer.

The major underpinning of an advanced algorithm is that a thorough knowledge of the process is required. This means reliable models must exist upon which the output of the controller is based. The main driving force for using such algorithms is that response times are much shorter than PID controllers and overshoot is practically nil.

## The Digital Computer and Discrete Control

The use of advanced control algorithms would be impossible without the digital computer. Such algorithms are characterized by multiple linear calculations which can only be handled by a computer in a reasonable amount of time needed for process control.

Since the digital computer is a discrete controller, Z-transforms are required for the transfer functions of the system to be controlled. In illustrating the use of an advanced algorithm, it is assumed that the Z-transform has been derived. Once the Z-transform has been found, the programming of the algorithm is relatively simple.

## Programming Algorithms

This discussion involves the implementation of an advanced algorithm. It is assumed that the algorithm is executed at a regular time interval.

1. Write output equation in terms of inputs and previously saved values.
2. Output the calculated value.
3. Save the necessary values for the next output and return from the subroutine.
4. Call the subroutine from within the main program at a regular interval. The **settimer**() and **timer**() functions can be used to measure a specific time interval.

### Programming Note

The control block whose number is the same as the timer number cannot be used as a time proportioned output controller. The timer is used when a time proportioned output is selected. In the example below, block 4 cannot have a time proportioned output, as the timer is used in the program.

#### Example

This example implements a control algorithm in C. The output equation for a system is

$$c = 3.9 \times dbase(30001) + 22.3 + 0.905 \times c_1 + 0.42 \times c_2 + 2 \times a_1$$

where: $c$ is the present output
$c_1$ is the last output
$c_2$ is the second last output
$a_1$ is the last input

The calculated value is output to register 40013. The control routine is called by using a simple timing loop.

```
#include <mriext.h>
#include <iohw.h>

#define PERIOD      10
#define DELAY_TIMER 4
#define CONTROL_OUTPUT  40013
#define PROCESS_INPUT   30001

void controlAlgorithm( void )
{
   static int output[3] = 0;  /* output values */
   static int input[2] = 0;   /* input values */

   /* Read the current inputs */

   input[0] = dbase( MODBUS, PROCESS_INPUT );

   /* Calculate and write the next output */

   output[0] = 3.9 * input[0] + 22.3 +
      0.905 * output[1] +
      0.42 * output[2] + 2.0 * input[1];
   setdbase( MODBUS, CONTROL_OUTPUT, output[0] );

   /* Save current values for next execution */

   input[1]  = input[0];
   output[2] = output[1];
   output[1] = output[0];
}

void main( void )
{
   /* Initialize the timer to count seconds */

   interval( DELAY_TIMER, 10 );
   settimer( DELAY_TIMER, 0 );

   /* Main loop */

   while (TRUE)
   {
      /* Execute at specified interval */

      if (timer( DELAY_TIMER ) == 0)
      {
         controlAlgorithm();
         settimer( DELAY_TIMER, PERIOD );
      }

      /* The rest of the program */
   }
}
```

# Appendix A: Transfer Function

The equation for the PID algorithm in continuous form is:

$$m = Ke + \frac{K}{T_i}\int_0^t e\,dt + KR\frac{dp}{dt} + m_s \qquad \text{Equation A-1}$$

Since the computer algorithm does not operate continuously, the discrete equivalents of the integral and derivative terms are taken:

$$m_i = Ke_i + \frac{KT}{T_i}\sum_{n=0}^{i} e_n - \frac{KR}{T}(p_i - p_{i-1}) + m_s \qquad \text{Equation A-2}$$

where: i denotes the current sampling time
$T$ is the sampling period

Now consider the output of the previous sampling period as shown in equation A-3.

$$m_{i-1} = Ke_{i-1} + \frac{KT}{T_i}\sum_{n=0}^{i-1} e_n - \frac{KR}{T}(p_{i-1} - p_{i-2}) + m_s$$

Equation A-3

Taking the backwards difference of equations A-2 and A-3 we have:

$$m_i - m_{i-1} = K(e_i - e_{i-1}) + \frac{KT}{T_i}e_i - \frac{KR}{T}(p_i - 2p_{i-1} - p_{i-2})$$

$$m_i = m_{i-1} + K(e_i - e_{i-1}) + \frac{KT}{T_i}e_i - \frac{KR}{T}(p_i - 2p_{i-1} - p_{i-2})$$

Equation A-4

Taking the Z transform of equation A-4 yields:

$$M(z) = z^{-1}M(z) + K(E(z) - z^{-1}E(z)) + \frac{KT}{T_i}E(z) - \frac{KR}{T}(P(z) - 2z^{-1}P(z) + z^{-2}P(z))$$

$$M(z) = KE(z) + \frac{KTE(z)}{T_i(1 - z^{-1})} - \frac{KR}{T}P(z)(1 - z^{-1})$$

Equation A-5

Equation A-5 should be used in any analysis of the transfer function of a system.